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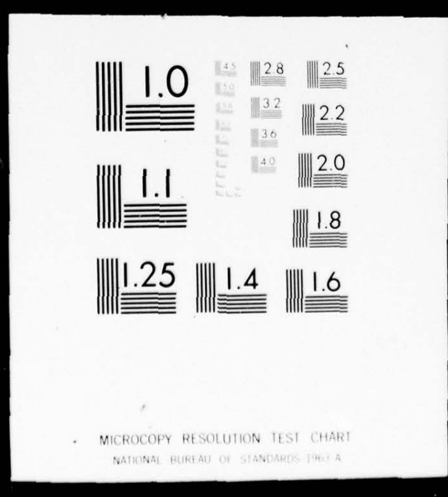

Report No. FAA-RD-77-84

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FEDERAL AVIATION ADMINISTRATION - FLORIDA INSTITUTE OF TECHNOLOGY WORKSHOP ON GROUNDING AND LIGHTNING PROTECTION

May 1977

Final Report

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
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16. Abstract

A state-of-art review and background research reveals a number of opinions as to the preferred techniques of grounding of electronic equipment and systems. These techniques become important when protection must be provided for transients induced by lightning,electromagnetic pulses (EMP), and other sources. The Systems Research and Development Service of the Federal Aviation Administration in conjunction with the Florida Institute of Technology conducted a workshop which brought together distinguished experts in the fields of grounding, lightning, transient protection and EMP protection. This report contains the papers presented at the workshop. This is the fourth workshop conducted on the subject. The papers presented at the 1974, 1975, and 1976 workshops are contained in Report No's. FAA-RD-74-147, FAA-RD-75-106, and FAA-RD-76-104.

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FINAL PROGRAM

FEDERAL AVIATION ADMINISTRATION/FLORIDA INSTITUTE OF TECHNOLOGY
WORKSHOP ON
GROUNDING AND LIGHTNING PROTECTION
MELBOURNE, FLORIDA
April 19-21, 1977

TUESDAY, APRIL 19th

Registration - Gleason Auditorium

Introductory Remarks - Dr. A. W. Revay, Jr., Associate Dean for Research Programs and Head, Electrical Engineering Department.

Welcome - Dr. J. P. Keuper, President, Florida Institute of Technology.

Opening Remarks - Mr. D. J. Sheftel, Director, Systems Research and Development Service, Federal Aviation Administration.

Announcements - Mr. R. M. Cosel, Florida Institute of Technology.

SESSION MODERATOR: Mr. R. Barkalow, Systems Research and Development Service, Federal Aviation Administration.

"Grounding the Underrated Destroyer, BEN FRANKLIN STYLE" - Mr. Marvin M. Frydenlund, Executive Director, Lightning Protection Institute, Harvard, Illinois.

"Lightning Protection" - Dr. Rodney B. Bent, Atlantic Sciences Corporation, Indian Harbour Beach, Florida.

"The Lightning Protection System at Tanegashima Space Center (TNSC)" - Mr. K. Hibi, Mr. T. Kurosaki, Mr. Y. Iida, Mr. A. Ogiso, National Space Development Agency of Japan.

"Protection from Lightning Induced Effects" - Mr. J. R. Stahmann, PRC System Services Company, Kennedy Space Center, Florida.

SESSION MODERATOR: Mr. O. M. Clark, General Semiconductor Industries, Inc.

"Geometric Models for Study of the Electrical Effects of Lightning" - Mr. F. A. Fisher, General Electric Company, Pittsfield, Massachusetts.

"Lightning Protection for Secondary AC Power Lines" - Mr. L. Becker, Kentron Hawaii, Ltd., Dallas, Texas.

"Protection of Components, Circuits and Systems" - Mr. R. Odenberg, Transtector Systems, Monterey Park, California.

"Transient Voltage Suppression Using Silicon Avalance Suppressors" - Mr. O. M. Clark, General Semiconductor Industries, Inc., Tempe, AZ.

Panel Discussion

WEDNESDAY, APRIL 20th

SESSION MODERATOR: Dr. M. D. Drake, Florida Institute of Technology

"EMP Protection Methods Using Silicon Avalanche Devices" - Mr. O. M. Clark, General Semiconductor Industries, Inc., Tempe, AZ.

"Bulk Electronic Surge Arrestor" - Mr. G. E. Keiser, Mr. L. Lesinki, GTE Sylvania, Needham, Massachusetts.

"Solid State Electronic Surge Arrestor (ESA)" - Mr. M. S. Cooper, Mr. J. J. Lee, GTE Sylvania, Needham, Massachusetts.

"Lightning Protection for Facilities Housing Electronic Equipment" - Mr. R. S. Smith, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia.

"Grounding Requirements for Electromagnetic Pulse (EMP) and Lightning Protection of Transportable Satellite Communications Terminals" - Mr. W. J. Getson, Harris Electronics Systems Division, Melbourne, Florida.

SESSION MODERATOR: Mr. H. Denny, Engineering Experiment Station, Georgia Institute of Technology.

"Investigation of Severe Noise Problems at Air Traffic Control Tower Locations" - Mr. J. Leahy, Federal Aviation Administration New England Regional Office; Dr. R. B. Bent, Atlantic Sciences Corporation, Indian Harbour Beach, Florida.

"Shielding and Grounding Topology for Interference Control" - Mr. E. F. Vance, Stanford Research Institute, Menlo Park, California.

"Theoretical Analysis and Design Techniques for Grounding to Accomplish EMI Control" - Mr. V. M. Turesin, Lockheed Missiles and Space Company, Sunnyvale, California.

"Survey of Grounding Practices at Major FAA Facilities" - Mr. J. Woody, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia.

"FAA Field Testing Methodology" - Mr. G. C. Apostolokis, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

Panel Discussion

THURSDAY, APRIL 21st

SESSION MODERATOR: Mr. William Jafferis, National Aeronautical and Space Administration, Kennedy Space Center.

"A System Grounding Approach for High Speed Digital Computer Generated Image (CGI) Simulation Devices/Trainers" - Mr. G. P. Condon, General Electric Company, Philadelphia, Pennsylvania.

"Design of Chassis Ground Networks Used in Large Scale Digital Simulator Systems" - Mr. G. W. Gowdeski, AAI Corporation, Baltimore, Maryland.

"Design Guide for the Utilization of Raised (Computer) Floor Systems as an Integral Part of the Grounding System" - Mr. R. N. Hokkanen, Naval Training Equipment Center (N-411), Orlando, Florida.

"Transient and Surge Protection of Computer Controlled Building Automation Equipment" - Mr. J. L. Howe and Mr. E. Dalman, Powers Regulator Company, Northbrook, Illinois.

Panel Discussion

"NASA Overview" - Mr. William Jafferis, NASA, Kennedy Space Center, Florida.

NASA Tour - Buses will depart from Gleason Auditorium for NASA Tour. This will combine a VIP overlook with an inside view of work and facilities involved in NASA's Lightning Protection Program.

GROUNDING THE UNDERRATED DESTROYER, BEN FRANKLIN STYLE

by

Marvin M. Frydenlund

Lightning Protection Institute

Harvard, Illinois

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

The American lightning protection industry had its beginning in 1755 when Franklin stated definitely for the first time that lightning rods were intended not only to "silently draw the electric fire" from the clouds, but also to intercept and ground any discharge. Lightning protection specifications began in 1762 when Franklin inspected the house of a Mr. West in Philadelphia, which had been struck and slightly damaged near the lightning ground. Franklin observed that "The rod should have been sunk deeper till it came to earth moister . . ."

This paper will trace the development of the lightning protection industry in America from that time until now, featuring the highlights of the industry's economic as well as technological progress, with particular emphasis on the development of standards. Industry practices in regard to the use of codes and practical application of standards will also be highlighted.

Basic changes in materials, parts, and other details will be covered as well as the gradual evolution in thinking in regard to the purposes of lightning protection systems. Today, the industry aims only to ground any lightning stroke; it does not attempt, as Franklin first said, to prevent a stroke from occurring.

Today, after a five-year period of recent change, the lightning protection industry has its first Certified Master Installers, Designers, Certified Systems, own installation codebook, and first graduates of a special lightning protection educational course.

The changes brought about by the new programs and the likely long-range effects of them will also be discussed.

GROUNDING THE UNDERRATED DESTROYER

BEN FRANKLIN STYLE

By Marvin M. Frydenlund
Managing Director
Lightning Protection Institute
Harvard, Illinois

FIGURE - 1

Benjamin Franklin, writer, publisher, first American postmaster general, statesman-patriarch of the Revolutionary cause, earned his first and greatest glory through his work with lightning and lightning protection. Because of it, he was an international folk hero 22 years before the Declaration of Independence, which he helped Thomas Jefferson write.

During seven years, from 1747 through 1753, Franklin created the three basic components of the North American lightning protection industry. He founded its science by identifying lightning as electricity; he devised its product by inventing the lightning rod; and he laid its technological foundation when he supervised the first lightning rod installations on houses in his hometown, Philadelphia.

FIGURE - 2

Buildings protected with Franklin Rods included the Warner House, still standing at Portsmouth, New Hampshire. On its roof is a lightning rod said to have been installed in 1762 under the eye of the inventor himself.

FIGURE - I

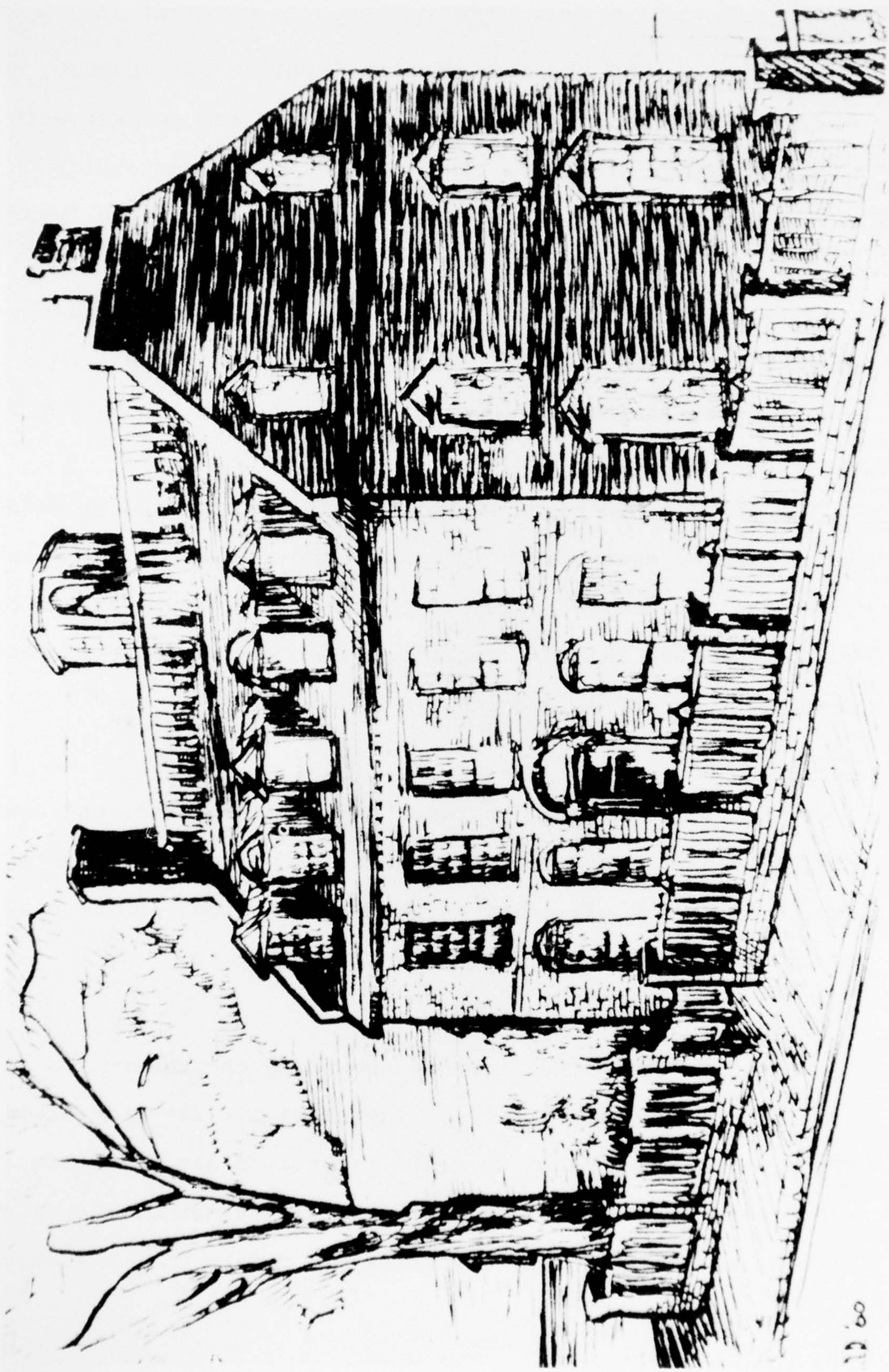


FIGURE - 2

FIGURE - 3

Franklin was at the same time an idealist philosopher, an original inventor, and a persuasive writer and speaker with an active sense of humor. In brief, he had great style. And he imprinted that style so clearly on the industry he founded that it is still visible today.

Compare a 1767 Franklin Rod installation to an ornamented system of 150 years later. Then compare both systems to a modern installation made by a Lightning Protection Master Installer in 1977.

The three basic parts -- points, conductors, and grounds, have remained essentially the same. The "power of the points", as Franklin sometimes referred to the point discharge phenomenon that determined the configuration of lightning rods, is sacrosanct to this day in America.

FIGURE - 4

Whatever its height, whatever the material used, and however plainly designed or ornamented, the sharply pointed lightning rod, or air terminal point as it is now called, is the essence of lightning protection, Ben Franklin style.

FIGURE - 5

To tell clearly the story of grounding the underrated destroyer, Ben Franklin style, requires a sketch of its 224-year history. The story began in 1753 when the first Franklin Rod installations were made in Philadelphia. The 224 years divide conveniently into seven periods, each beginning and ending with a particularly

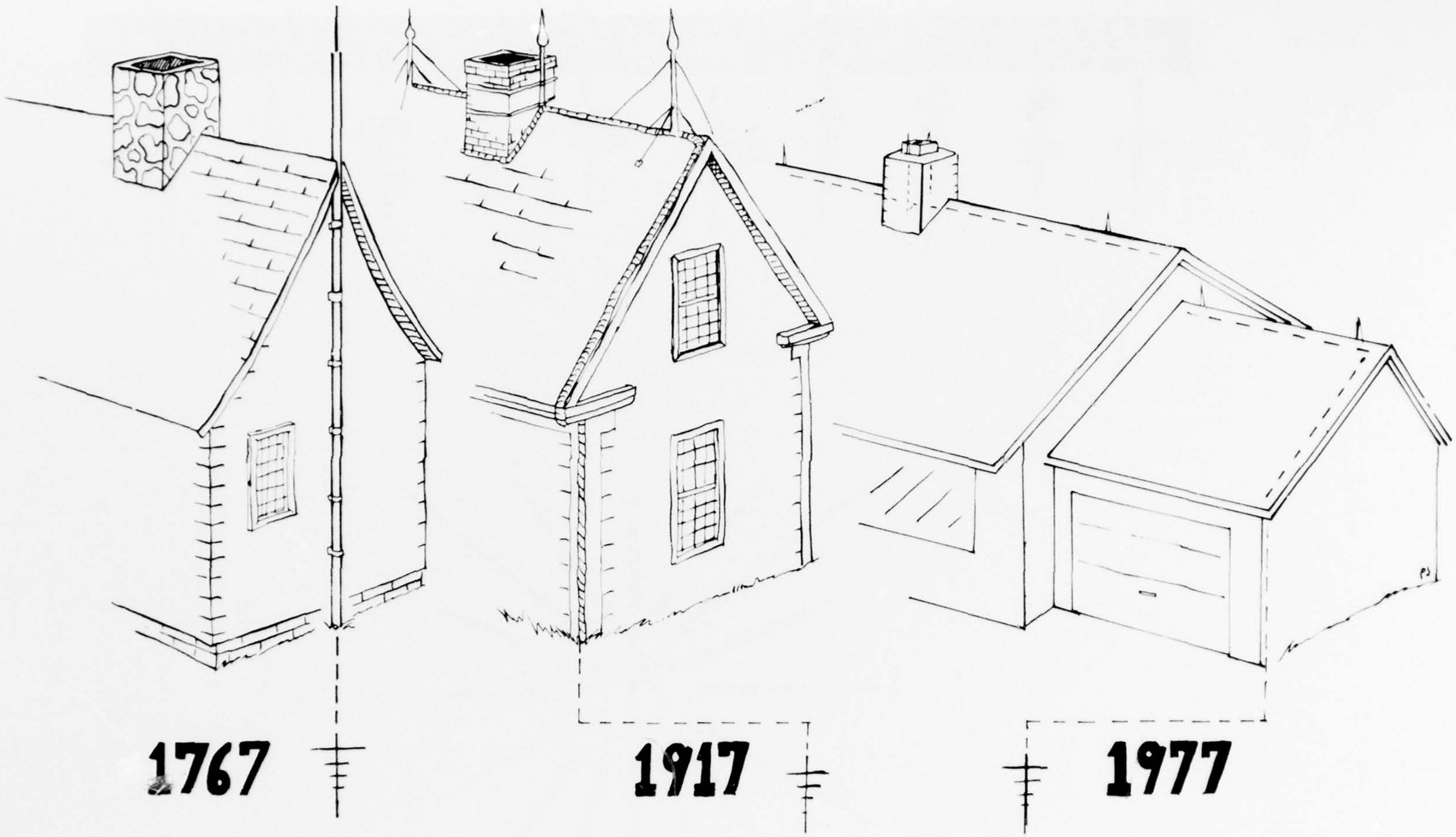


FIGURE - 3

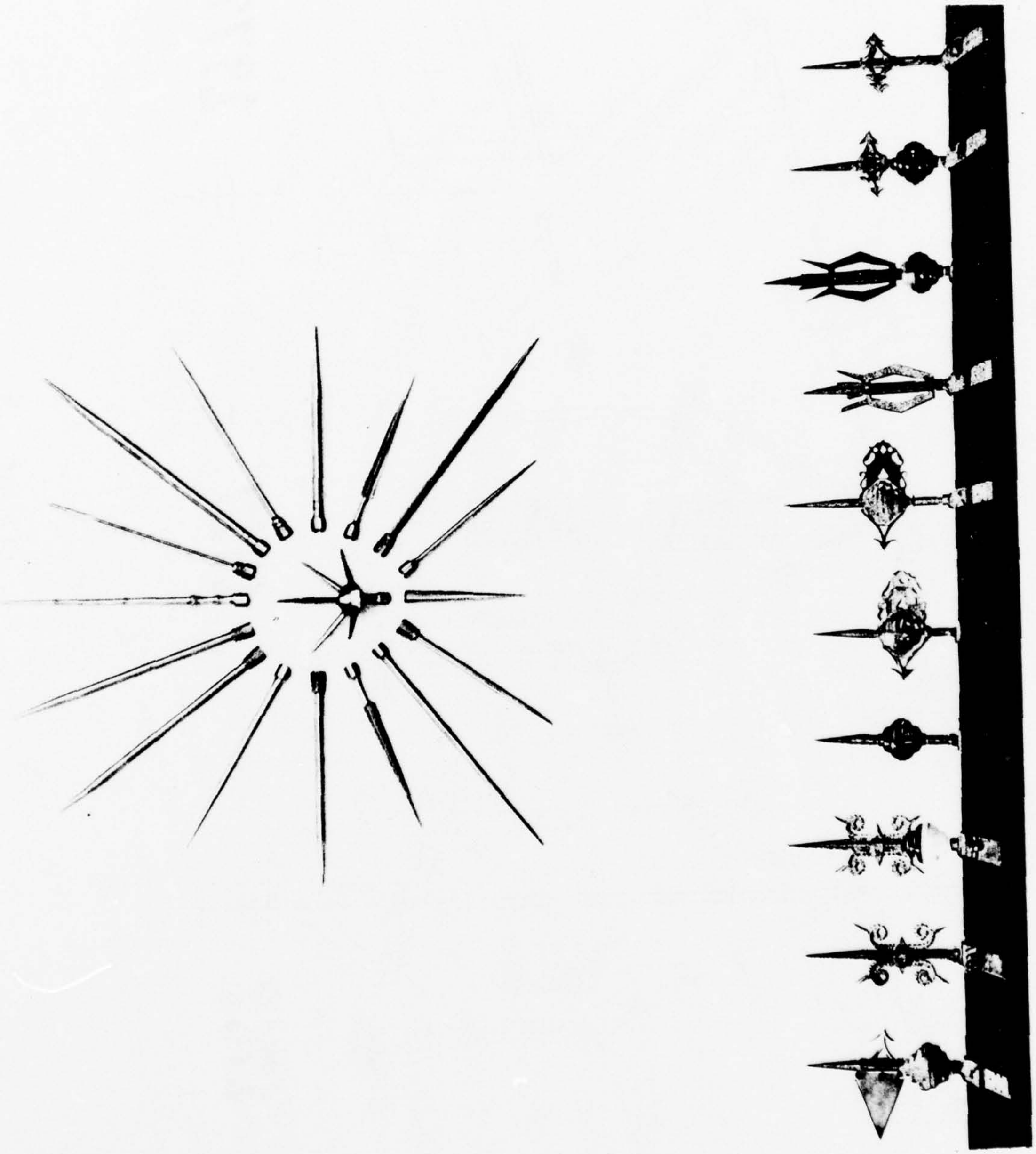


FIGURE - 4

FIGURE - 5

significant event.

Period 1 was the Franklin Era. Its 15 years were dominated by the inventor himself. After 1753 he gave lightning protection less and less attention, and made his last noteworthy contribution to it in 1767.

FIGURE - 6

For want of a better term, Period 2 can be called the Hiatus. It was a leaderless, 115-year stretch between the influences of Ben Franklin and Thomas Edison. Edison inspired a spate of lightning research activity when he launched the electric power industry, with its lightning-caused outages and other problems.

FIGURE - 7

Period 3, the Organizational Era, began with a reassertion of lightning protection leadership, not by a strong individual this time, but by an international group which convened a Lightning Rod Conference in 1882 at London, England. Conferees wrote a set of international consensus specifications for lightning protection.

This Era climaxed 22 years later with another, even more significant group action, by the National Fire Protection Association. In 1904, the NFPA adopted the first edition of what later became the American national consensus code, NFPA No. 78.

FIGURE - 8

Period 4 was colorful, active, and unfortunately for the cause of proper lightning protection, freewheeling. Many names come to mind that might fit the 37-year period between 1904 and

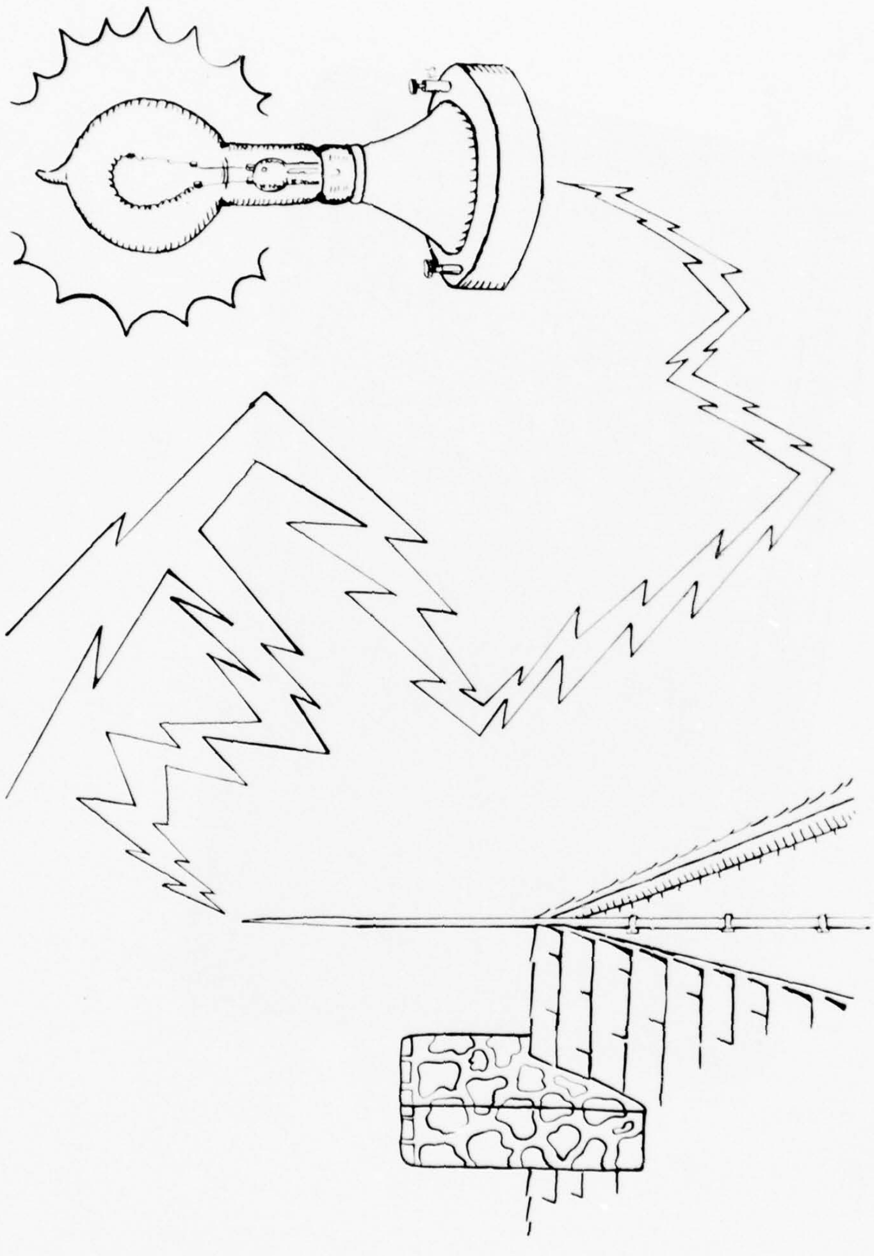


FIGURE - 6

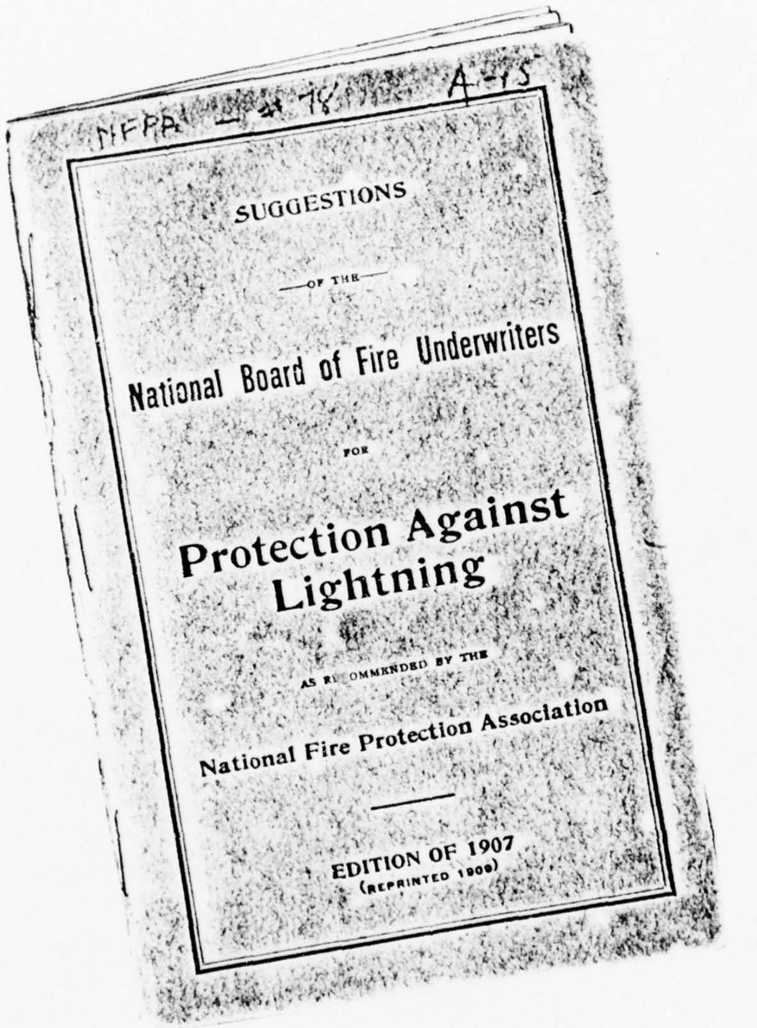

NFPA
A-15
SUGGESTIONS
OF THE
National Board of Fire Underwriters
FOR
Protection Against Lightning
National Fire Protection Association
EDITION OF 1907

FIGURE - 7

FIGURE - 8

1941, but the one that seems to wear best is Lightning Rod Heyday.

The era began with a promotional boost by the NFPA installation code, helped along by rate credits granted by farm mutual insurance companies on rodded buildings.

The industry mushroomed in those early years of this century. At one point, about 100 companies claimed to be lightning rod manufacturers. Some of the more successful salesmen were chauffeured by their own wagon drivers. Installer crews followed in their wake with other wagons heavily loaded with materials.

FIGURE - 9

Competitive claims grew more and more fanciful. Ethics and workmanship suffered as some of the less successful manufacturers and installers fell behind, then fought to catch up with the leaders. In 1923, Underwriters Laboratories created the UL Master Label Service to inspect factory materials and the quality of installations.

Houses and barns constituted the major share of the Heyday market. The Great Depression of the 1930's cooled promotional activities of survivors of the intense competition in the 1920's. Only a handful of better managed manufacturing companies made it through the depression. The period ended with the outbreak of World War II.

FIGURE - 10

In 1941, America mobilized for World War II. Manufacturers and installers of lightning protection systems entered the

FIGURE - 9

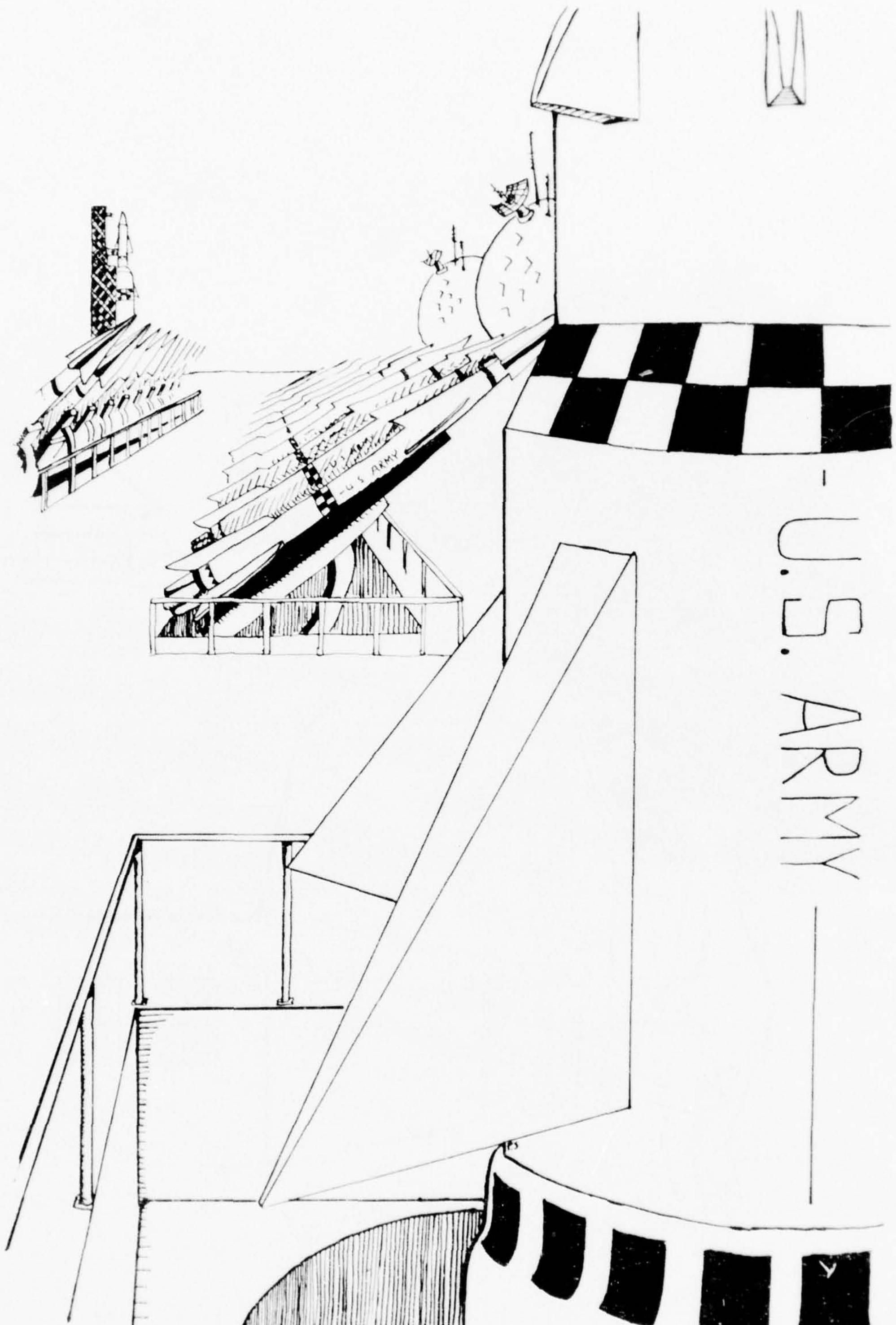


FIGURE - 10

Military Era. The farmer ceased to be the largest customer. His place was taken over by Army and Navy engineers and government architects. For 13 years, from 1941 through the Second World War, the Korean War and its aftermath, and until 1955, a large share of business was protection of arsenals, defense plants, munitions dumps, other military and government facilities, and finally, defense missile sites.

FIGURE - 11

In 1955, the Lightning Rod Manufacturers Association found it needed to re-educate the consumer market. The Association took the most significant step since 1904, forming the Lightning Protection Institute. Of eight companies at that time which were full-fledged specialized manufacturers of lightning protection materials and parts, six were charter members of the Institute.

They were Thompson Lightning Protection, Inc., St. Paul, Minnesota, which was the organizing company; The Carl Bajour Company, Inc., Jonesboro, Arkansas; Independent Protection Co., Inc., Goshen, Indiana; National Lightning Rod Company, St. Louis, Missouri; Security Lightning Rod Company, Burlington, Wisconsin; and West Dodd Lightning Conductor Corporation, Goshen, Indiana.

National and Security have since gone out of business. Although membership has remained open, the four surviving Manufacturer Members supported the Institute alone until 1975. Most of the Institute's budget went for educational materials and public relations projects during its first 20 years. In the beginning, old-fashioned "scare tactics" were still in vogue. This period

More People Are Injured

by **LIGHTNING**

than by

Floods - Tornadoes - Hurricanes

FIGURE - 11

can be termed the Educational Era.

FIGURE -12

The year 1975 marked the beginning of the current Era of Professionalism. Time may prove 1975 the most significant year for lightning protection since 1753. Three events took place that year:

1. The Lightning Protection Institute published the first industry-produced installation code, LPI-175.

2. The Institute introduced a testing and certification program for Master Installers, Designers, and Journeyman Installers.

3. The LPI support base was broadened by creation of a new sponsorship category, Contractor Members and their employees.

FIGURE - 13

The title term, "Underrated Destroyer" was suggested by a cover article in the April, 1976 issue of NOAA, magazine of the National Oceanic and Atmospheric Administration. That article, by Edwin Weigel, "Lightning: The Underrated Killer", described a 34-year study that showed lightning responsible for 7,000 deaths in the United States, 55 percent more than were killed by tornadoes, and 41 percent more than died in hurricanes and floods combined. This even though lightning as a cause of death is underrated.

Mr. Weigel explained that because lightning usually kills one person at a time, it does not attract nationwide attention as do the multiple-death occurances of far less frequent

THE LIGHTNING PROTECTION INSTITUTE

HARVARD, ILLINOIS

This is to certify that

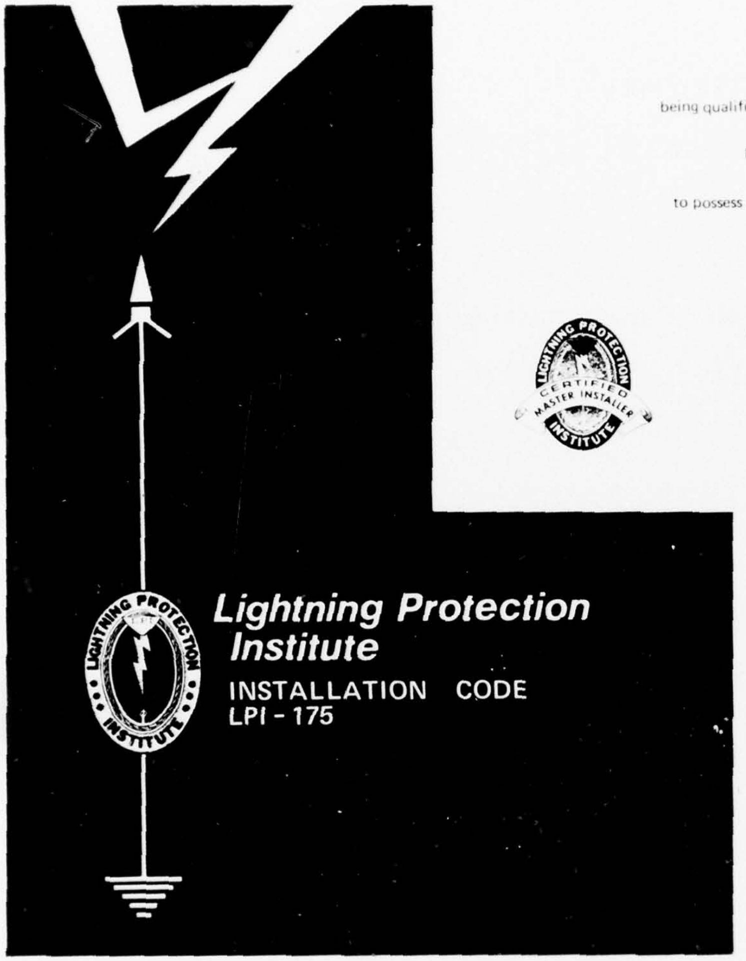
being qualified by experience and found upon examination
given December first and second
Nineteen hundred and seventy-five,
at Columbus, Ohio
to possess advanced knowledge and expert abilities, is a

MASTER INSTALLER

of lightning protection systems.
Attest this sixteenth day of July,
Nineteen hundred and seventy-six.

Executive Director

of the Board of Directors



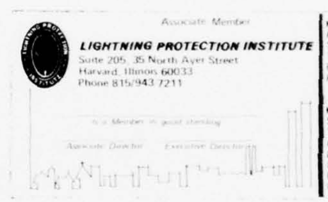


FIGURE - 12

Lightning kills more people in the United States than tornadoes, floods or hurricanes.

During the 34-year period that ended Jan. 1, 1974, lightning was responsible for the deaths of about 7,000 Americans, or 55 percent more than were killed by tornadoes and at least 41 percent more than were killed by hurricanes and floods combined.

This total of lightning deaths is undoubtedly conservative, statistics-gatherers agree. Many are not included in national summaries because lightning usually kills only one person at a time. Occasionally there are two deaths from a single stroke; rarely as many as three or more (although multiple numbers of injured from a single bolt are not uncommon.)

Lightning deaths don't attract nationwide attention, as do the more-spectacular hurricanes, tornadoes, and floods, which may kill hundreds and cause many millions of dollars in property damage in a single episode.

Paradoxically, though, the statistics available indicate that the annual numbers of lightning deaths in recent years have been much lower than death tolls earlier in this century, even though the U.S. population has increased greatly. There were, for example, 120 per year for the decade ending with 1973, compared to an average of 329 per year during the decade of the 1940's. This apparent drop is misleading. To understand why, it's necessary to know a little about the complex subject of natural-disaster statistics.

Annual death tolls for hurricanes, tornadoes and floods are prepared by NOAA's National Climatic Center in Asheville, N.C., and published in its annual "Climatological Data, National Summary." But lightning death tolls are not included in this summary, even though the Center receives each month tallies of lightning deaths and injuries from field offices of the National Weather Service and publishes them in a monthly periodical called "Storm Data."

Why? "Because we are confident that any annual total of lightning deaths we could provide would be too low for the nation as a whole," says Marvin Burley, chief of the Cooperative Data Branch of the Climatic Center. "Weather Service field units can't possibly learn about all of the lightning fatalities in their areas of responsibility. Their principal assignment is forecasting the weather, and this takes precedence over tabulating storm deaths, injuries and damage, although they do the best they can."

Then who does supply lightning fatality statistics for the nation?

For years, this information has been provided by the National Center for Health Statistics, U.S. Public Health Service, Department of Health, Education and Welfare.

The Center bases its totals on causes of death listed on certificates signed by physicians.

A logical first reaction is that these death certificates should provide an even more accurate count than other sources, since such certificates are prepared one by one, by skilled medical examiners. But there is a flaw in this reasoning, based on a change that took place in the Health Service's rules for tabulating lightning deaths more than 20 years ago.

According to Marvin D. Magnuson, former Regional Climatologist for the Western Region of the National Weather Service, "Statistics compiled by the Public Health Service prior to 1953 contain other causes of death, such as those resulting from fires started by lightning. In 1953, Health Service coding rules were modified so that all deaths caused by any accident that was secondary to the effects of lightning were to be assigned to that cause rather than lightning."

Towering cumulonimbus cloud below, with characteristic anvil top, is the type that unleashes lethal discharges of lightning such as in the time exposure at right.

Photo: Marc Brock, New Mexico Institute of Mines and Technology

LIGHTNING: The Underrated Killer

BY EDWIN P. WEIGEL

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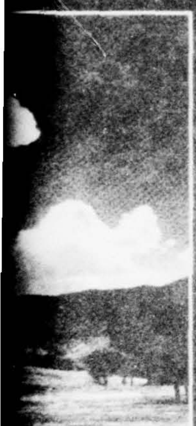


Photo: Marx Brook, New Mexico Institute of Mining and Technology

Photo: Westinghouse

FIGURE - 13

tornadoes, floods, and hurricanes. And, many lightning fatalities are attributed instead to the immediate death cause, such as asphixiation in a lightning-caused fire, or electrocution from a lightning-downed powerline.

Lightning also destroys more property than is generally blamed to it. Again one reason is that lightning usually ignites only one building at a time. And smaller losses, such as destruction of an electrical system or an appliance, or a tree, do not find their way into public records. Such small lightning losses are so frequent and scattered that only a portion of them could be recorded by any existing loss-gathering method or organization.

When an estimate is made that lightning causes a certain amount of property loss annually in the United States, the figure is based on fragmentory statistics. Thus, the title.

FIGURE - 14

Technological progress of lightning protection from 1753 to 1977 can be traced in eight steps.

The first systems installed in Philadelphia during 1753 were described in Franklin's POOR RICHARD'S ALMANACK of that year:

"The method is this: provide a small iron rod (it may be made of rod-iron used by the nailers) but of such length, that one end being three or four feet in the moist ground, the other may be six or eight feet above the highest part of the building. To the upper end fasten about a foot of brass wire, the size of a common knitting needle, sharpened to a fine point; the rod

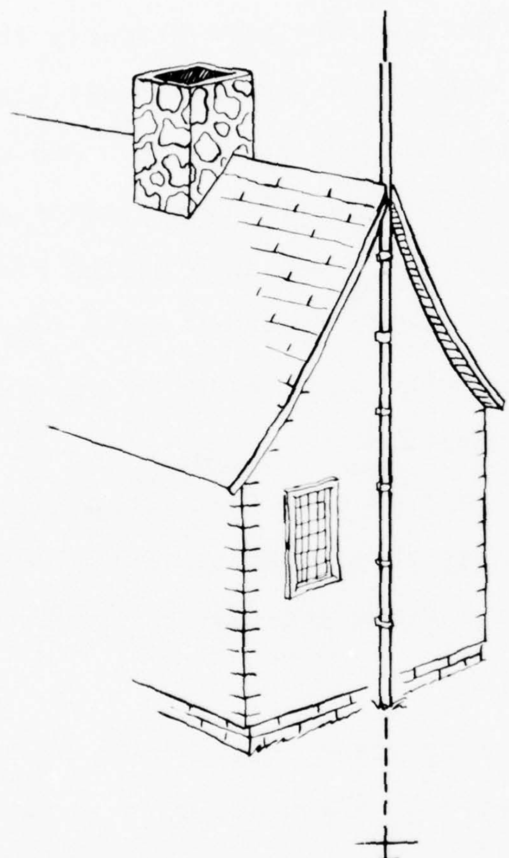


FIGURE - 14

may be secured to the house with a few small staples. If the house or barn be long, there may be a rod or point at each end, and a middling wire along the ridge from one to the other."

Note that for a small house, lightning protection consisted of only two parts -- a foot of brass wire attached to one long rod, attached to the wall by a few staples. The two ground rods and the "middling wire" Franklin mentioned were the beginning of our present system of grounds, conductors and air terminals. Even then, in 1753, Franklin recognized the limited protective range of a single rod. The presence of that phrase, "middling wire", in Franklin's original announcement is remarkable evidence that lightning protection circa 1977, American style, is lightning protection, Ben Franklin style.

FIGURE - 15

In 1760, Franklin inspected a rodded house belonging to a Mr. West in Philadelphia which had been struck. The tip of the rod was melted, but the only harm done was some slight damage to the foundation. Franklin wrote that, "The rod should have been sunk deeper, so as to come to earth moister."

In September, 1767, a description by Franklin indicated three refinements. The foot of brass wire had been done away with. Instead, the tip of the iron lightning rod itself was tapered "...to a fine sharp point". Second, the point was protected with "...gilt to prevent its rusting".

Finally, Franklin wrote, "The lower end of the rod should enter the earth so as to come at the moist part, perhaps two

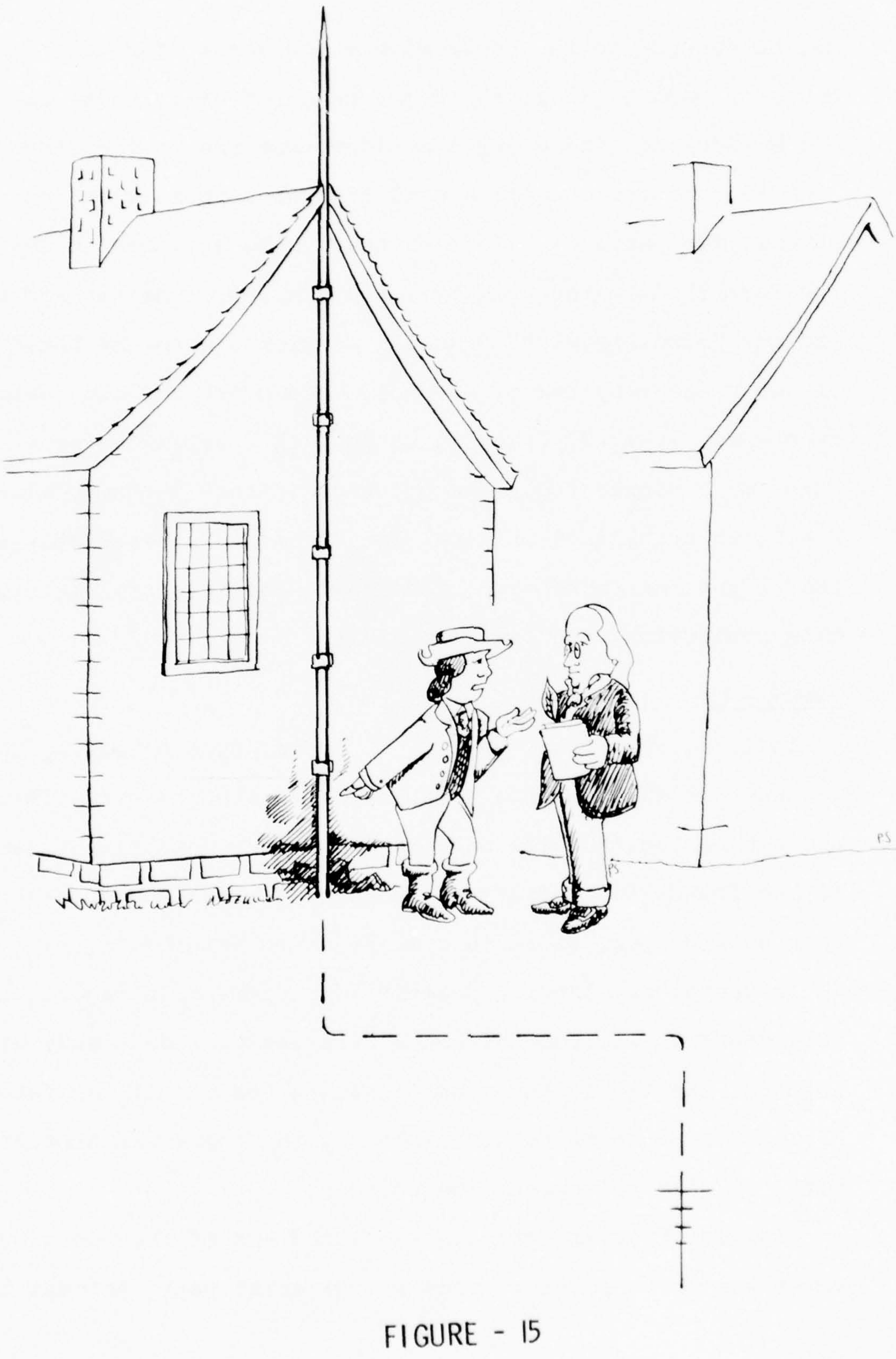


FIGURE - 15

to three feet; and if bent when under the surface so as to go in a horizontal line six or eight feet from the wall, and then bent again downwards three or four feet, it will prevent damage to any of the stones of the foundation."

FIGURE - 16

The report of the London Lightning Rod Conference of 1882 highlighted seven changes, though more had been made: (1) copper rods were recommended instead of iron; (2) minimum weights were agreed upon for conductors of copper and of iron; (3) joints were to be kept to a minimum and soldered; (4) earth connections to iron gas and water mains were specified; (5) the use of buried earth plates was suggested; (6) the cone of protection principle afforded by a rod was detailed; and (7) it was specified that internal and external masses of metal were to be connected to earth or to the lightning conductor.

FIGURE - 17

Quality control was added in 1923, when Underwriters Laboratories, Inc. created the Master Label service for lightning protection systems. This provided in-factory and on-site third-party inspection to determine that materials and installation were in accordance with the current edition of the NFPA code.

By 1923, lightning rods were being braced according to specifications. They were also ornamented with colored glass balls and weathervanes. The code called for 25-ft. minimum spacings between rods, and other size, spacing, and fastening requirements were essentially the same as they are today.

FIGURE - 16

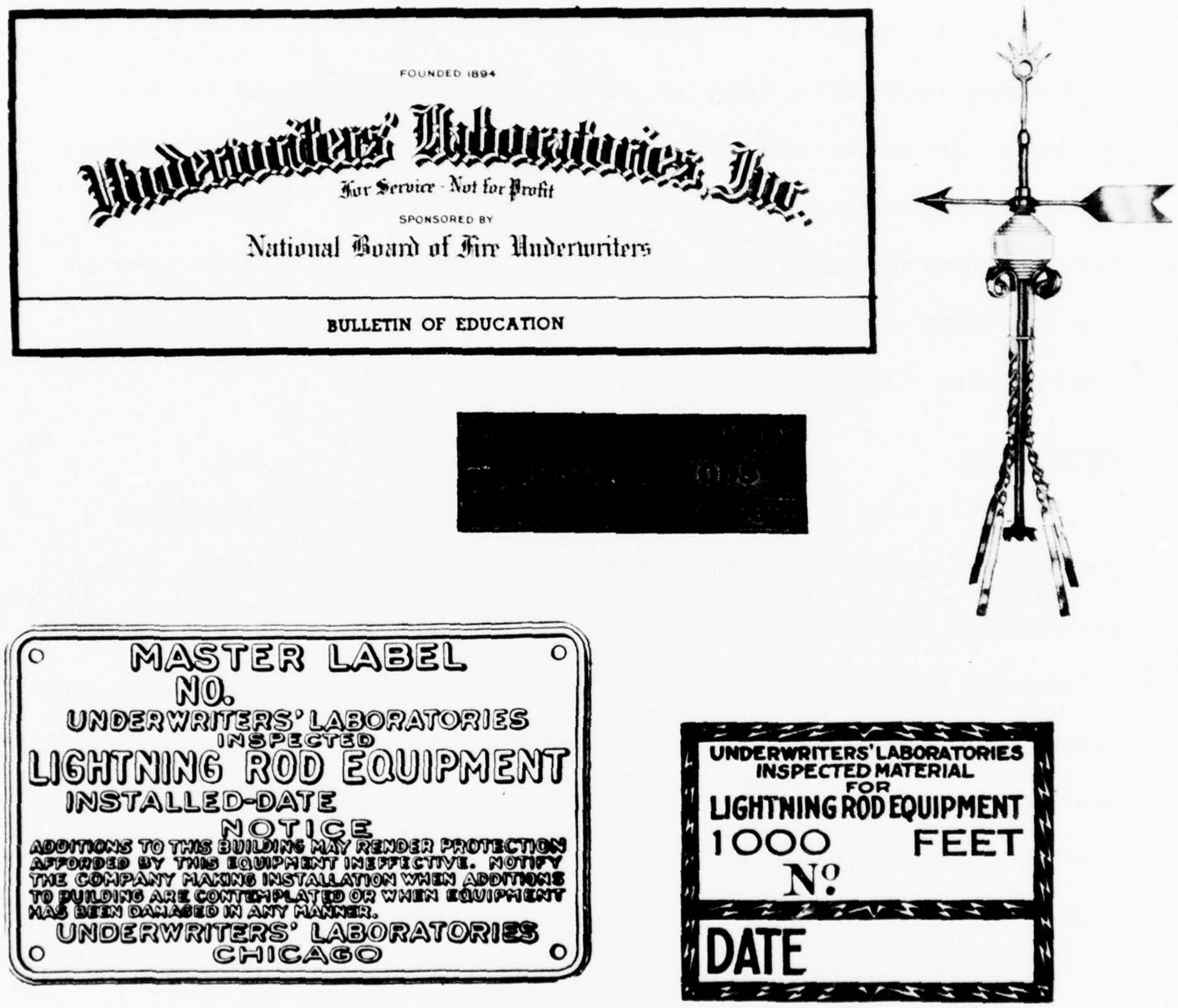

FOUNDED 1894
Underwriters' Laboratories, Inc.
For Service - Not for Profit
SPONSORED BY
National Board of Fire Underwriters
BULLETIN OF EDUCATION
MASTER LABEL
NO.
UNDERWRITERS' LABORATORIES
INSPECTED
LIGHTNING ROD EQUIPMENT
INSTALLED-DATE
NOTICE
ADDITIONS TO THIS BUILDING MAY RENDER PROTECTION AFFORDED BY THIS EQUIPMENT INEFFECTIVE. NOTIFY THE COMPANY MAKING INSTALLATION WHEN ADDITIONS TO BUILDING ARE CONTEMPLATED OR WHEN EQUIPMENT HAS BEEN DAMAGED IN ANY MANNER.
UNDERWRITERS' LABORATORIES
CHICAGO
UNDERWRITERS' LABORATORIES
INSPECTED MATERIAL
FOR
LIGHTNING ROD EQUIPMENT
1000 FEET
No
DATE

FIGURE - 17

Copper cable had come into general use, and the terms rope lay, twisted, and braided cable were familiar to installers. Aluminum, first available in 1866, came into use in lightning protection slowly. It still is a lower-cost substitute for preferred copper.

Ground rods were sunk to 10-ft. depth and spaced at 100-ft. or less, in moist clay soil. Counterpoise grounding systems had been introduced for less conductive soils. Lightning surge arresters had been introduced shortly after the turn of the century, but were not yet in general use with farm and residential lightning rod systems.

FIGURE - 18

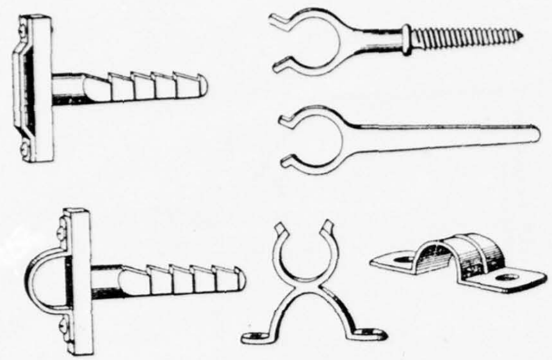
In 1947, the NFPA published its sixth revised lightning protection code, including for the first time Part III, "Protection of Structures Containing Flammable Liquids and Gases."

Short, neutral color, inconspicuous air terminal points were being promoted. The tall, old-fashioned, ornamented rods that were so popular in the Heyday Era had fallen out of disfavor, particularly with architects. The industry itself stopped referring to lightning rods, renaming them air terminals.

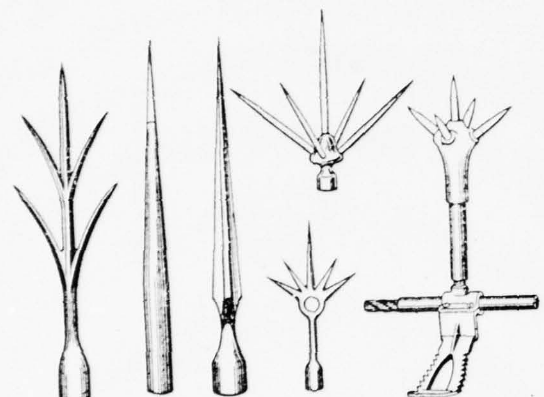
The state of the art of grounding the thunderbolt, Ben Franklin style, circa 1947, is depicted in some detail in that year's printing of the code, NFPA-78.

FIGURE - 19

We have just rewritten the NFPA Code to fit O.S.H.A.'s requirements regarding mandatory and permissive terms. The



Fasteners and Supports



Air Terminals

The edge of the roof is the part most likely to be struck on flat-roofed buildings. On large flat and gently sloping roofs it is desirable to erect air terminals at points of intersection of lines dividing the surface into rectangles not exceeding 50 feet (15.3 m) in length.

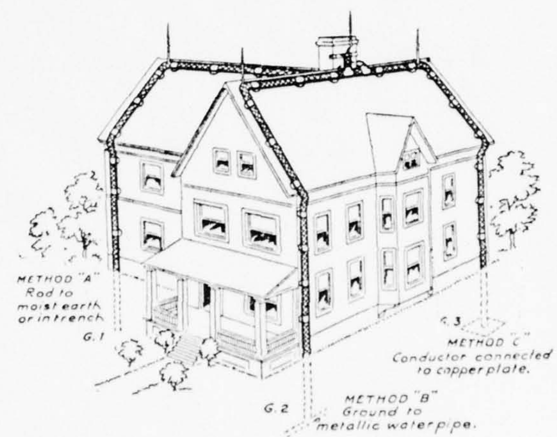
(*e*) *Coursing of Conductors.*—Conductors shall in general be coursed over the roofs and down the corners and sides of buildings in such a way as to constitute as nearly as local conditions will permit, an enclosing network.

(*f*) *Roof Conductors.*—Roof conductors shall be coursed along contours, such as ridges, parapets, and edges of flat roofs, and where necessary over flat surfaces, in such a way as to join each air terminal to all the rest.

Roof conductors surrounding decks, flat surfaces, and flat roofs, shall be connected to form a closed loop.

(*g*) *Down Conductors.*—Down conductors shall preferably be coursed over the extreme outer portions of buildings, such as corners, due consideration being given to the best places for making ground connections, and to the location of air terminals.

(*h*) *Obstructions.*—Horizontal conductors shall be coursed around chimneys, ventilators, and similar obstructions in a horizontal plane and without abrupt turns.



Typical Installation on Large Dwelling

FIGURE - 18

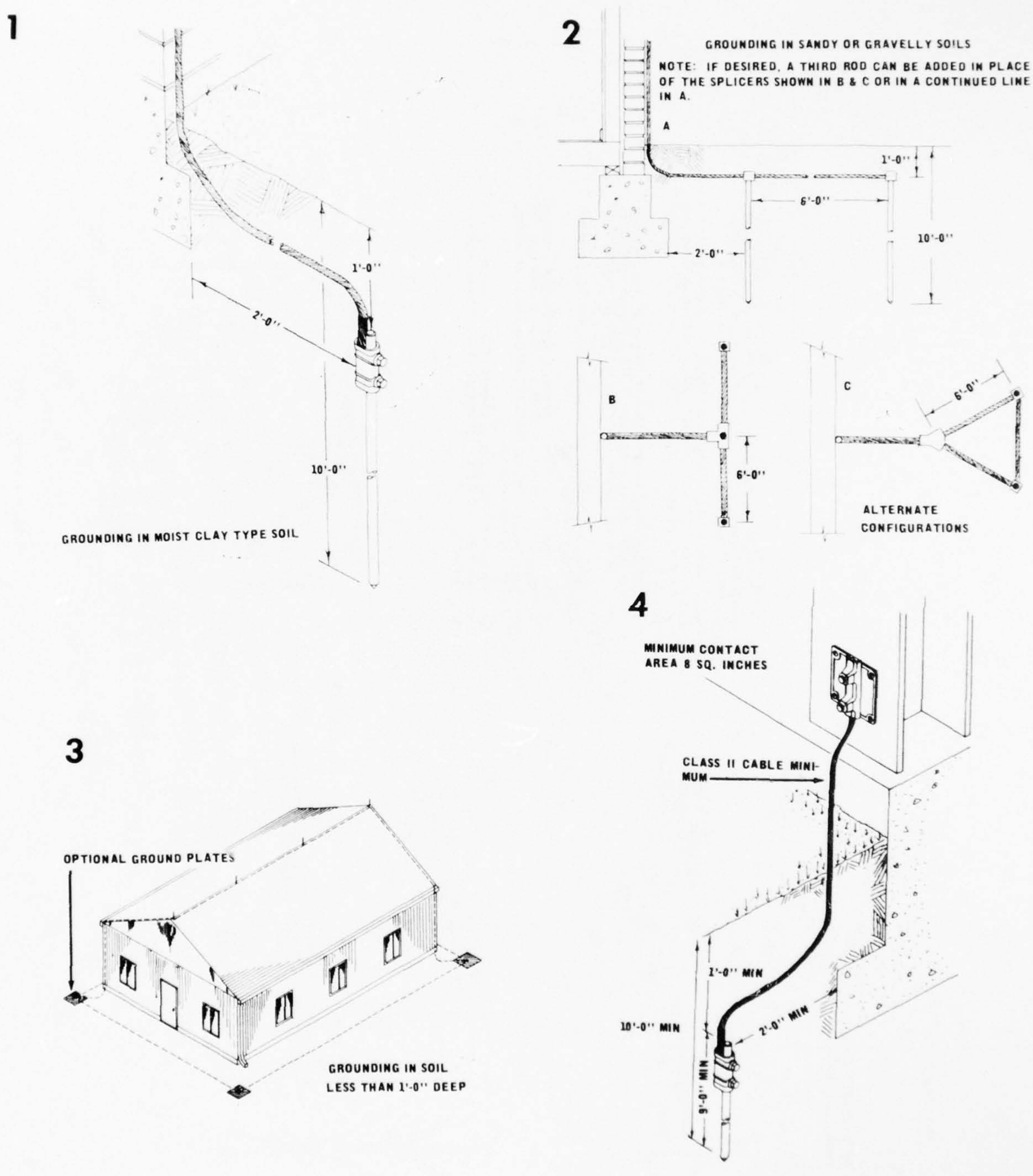

1
1'-0''
2'-0''
10'-0''
GROUNDING IN MOIST CLAY TYPE SOIL
2
GROUNDING IN SANDY OR GRAVELLY SOILS
NOTE: IF DESIRED, A THIRD ROD CAN BE ADDED IN PLACE OF THE SPLICERS SHOWN IN B & C OR IN A CONTINUED LINE IN A.
A
1'-0''
6'-0''
10'-0''
2'-0''
B
6'-0''
C
6'-0''
ALTERNATE CONFIGURATIONS
3
OPTIONAL GROUND PLATES
GROUNDING IN SOIL LESS THAN 1'-0'' DEEP
4
MINIMUM CONTACT AREA 8 SQ. INCHES
CLASS II CABLE MINI-MUM
1'-0'' MIN
2'-0'' MIN
10'-0'' MIN
9'-0'' MIN

FIGURE - 19

current state of the art in lightning protection grounding is illustrated in drawings adopted by the NFPA Code Committee from the LPI document, LPI-175.

1. Grounding in moist clay type soil requires a minimum of two copper-clad rods sunk to 10-ft. depth for any small building, with an additional rod for each added 100-ft. of perimeter. The rod must be 2-ft. out from the foundation, quite a bit less than Ben Franklin suggested 210 years ago.

2. Grounding in somewhat higher resistance soils with sand or gravel requires the use of additional rods in each ground location.

3. When soil is less than a foot deep, counterpoise grounding is specified. Standard copper lightning conductor, which must be at least 187½ pounds per thousand feet, is used to encircle the building. Copper ground plates at each corner are optional.

4. When a building has electrically continuous steel framing, air terminals are bonded directly to the steel framework by conductors leading through the roof or coping walls. The steel columns may serve as down conductors. Ground connections are usually made at every other column, but shall never be spaced at more than 60-ft.

FIGURE - 20

The Institute code, LPI-175, was among the reference documents in writing and illustrating the new NFPA code, and there is some overlapping of code committee membership. LPI-175 is

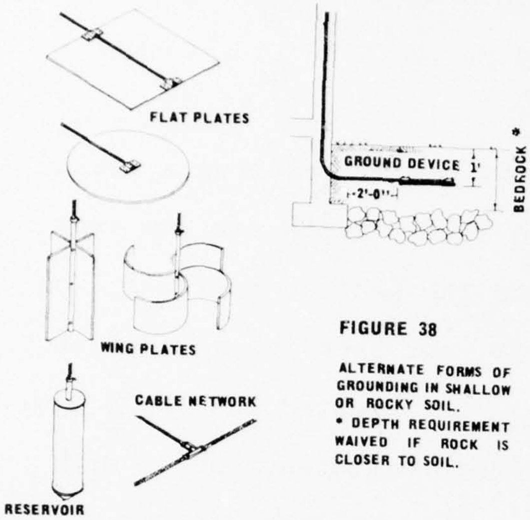


FIGURE 38

ALTERNATE FORMS OF GROUNDING IN SHALLOW OR ROCKY SOIL.
*** DEPTH REQUIREMENT WAIVED IF ROCK IS CLOSER TO SOIL.**

SECTION VIII MARKING AND MAINTENANCE

MAINTENANCE CHECK

196. An annual visual check shall be made by the owner or his designated agent of the total system. Typical check points, as shown in Figure 41 are:

1. All *air terminals* to assure that none are bent, cracked, broken or otherwise damaged, or that the cable connection is loose or damaged.
2. All *bonds to metal bodies*. Are they still tight; any physical damage; any sign of removal and improper reattachment; any new equipment added and not bonded?
3. **Tee-splicers and other connectors.** Still tight; all leads firmly connected; any loose ends?
4. **Through-roof connectors.** All connections firm; all roof conductors attached to down conductors?
5. **Secondary service arresters.** Are all leads intact? arrester body undamaged?
6. **Cable holders.** Check that all holders and similar attachments are still firmly attached, spaced properly (at 3'0" on centers), any new added runs are secured properly.
7. **Grounds.** Are down conductors undamaged and still tightly attached; any evidence of damage; fittings still sound, not cracked, bolts unbroken? If there is any evidence of mechanical damage to the system or any construction work or additions, grounds in the immediate area should be carefully checked.

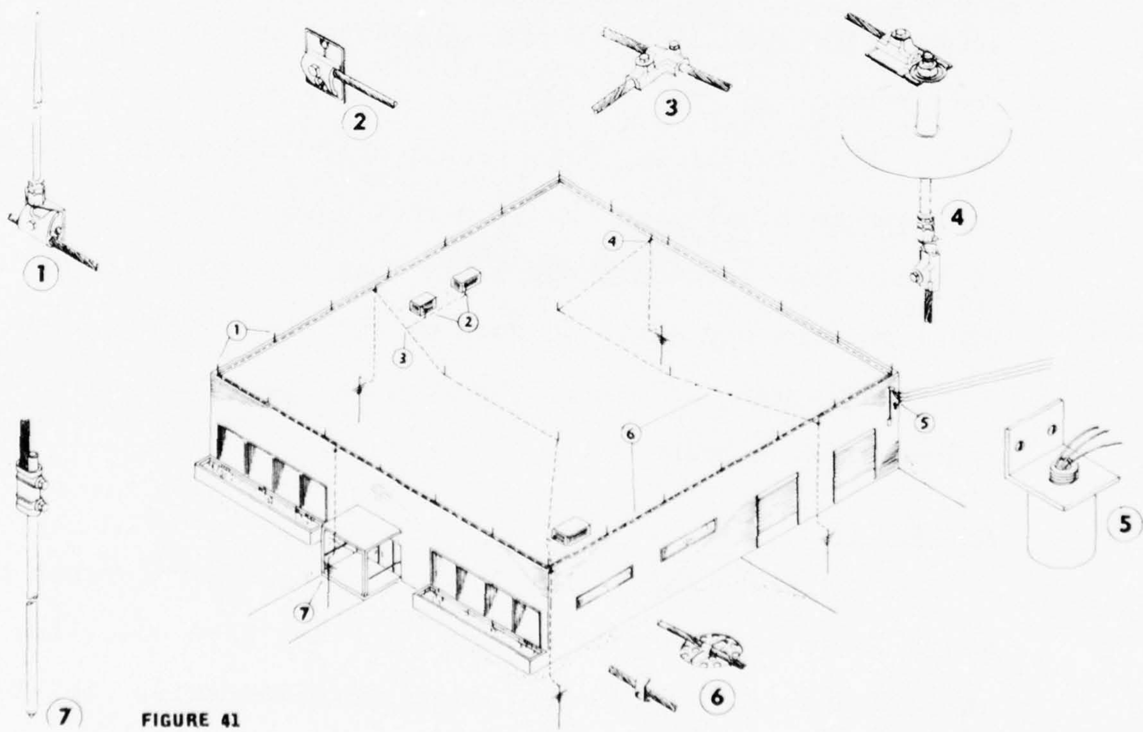


FIGURE 41

FIGURE - 20

limited to protection of ordinary and high-rise buildings, smokestacks, and trees, but goes into greater detail in those areas than will the 1977 NFPA document.

For example, alternate forms of grounding in shallow or rocky soil are illustrated. So are air terminal, conductor, and ground requirements for saw tooth roofs and domed or curved structures.

Code LPI-175 introduced a post-installation inspection and maintenance procedure, requiring an annual inspection.

When losses have occurred to systems installed under UL Master Label requirements, faults have been traced to physical damage, deterioration, or failure to extend the lightning protection system to cover an addition to the building or a new object on the roof. Most such faults will be caught by annual inspection.

FIGURE - 21

In summary....

In 1753, Ben Franklin installed lightning rod systems that had only two parts -- a sharpened copper wire at the top and a long iron rod that served both as ground conductor and ground.

In 1977, lightning protection systems which have six mechanical parts are: (1) a roof system of air terminals; (2) conductors; (3) grounding system; (4) bonds to metal bodies within 6-ft. of a conductor; (5) surge arresters; and (6) a separate system for any tree taller than the protected building and within 10-ft. of it.

A full-line manufacturer can supply more than 500 different

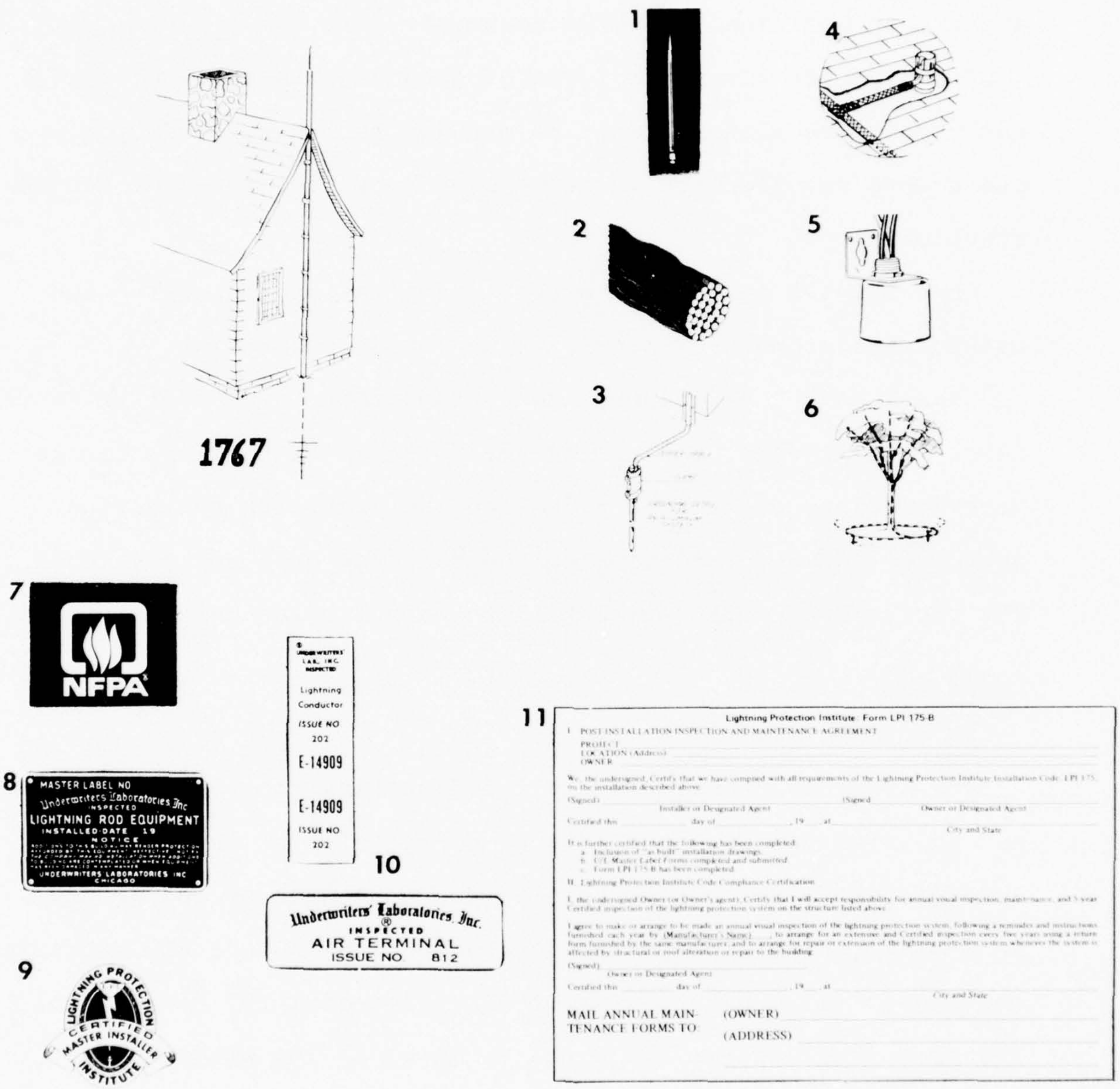

1767
1
2
3
4
5
6
7
NFPA
8
MASTER LABEL NO
Underwriters Laboratories Inc
INSPECTED
LIGHTNING ROD EQUIPMENT
INSTALLED DATE 19
NOTICE
UNDERWRITERS LABORATORIES INC
CHICAGO
9
LIGHTNING PROTECTION INSTITUTE
CERTIFIED MASTER INSTALLER
UNDERWRITERS' LAB. INC. INSPECTED
Lightning Conductor
ISSUE NO 202
E-14909
E-14909
ISSUE NO 202
10
Underwriters' Laboratories, Inc.
INSPECTED
AIR TERMINAL
ISSUE NO 812
11
Lightning Protection Institute Form LPI 175-B
I POST INSTALLATION INSPECTION AND MAINTENANCE AGREEMENT
PROJECT
LOCATION (Address)
OWNER
We, the undersigned, Certify that we have complied with all requirements of the Lightning Protection Institute Installation Code LPI 175, on the installation described above
(Signed) (Signed)
Installer or Designated Agent Owner or Designated Agent
Certified this day of , 19 at
City and State
It is further certified that the following has been completed:
a. Inclusion of "as built" installation drawings.
b. U.L. Master Label Forms completed and submitted.
c. Form LPI 175-B has been completed.
II. Lightning Protection Institute Code Compliance Certification
I, the undersigned Owner (or Owner's agent), Certify that I will accept responsibility for annual visual inspection, maintenance, and 5 year Certified inspection of the lightning protection system on the structure listed above.
I agree to make or arrange to be made an annual visual inspection of the lightning protection system, following a reminder and instructions furnished each year by (Manufacturer's Name) , to arrange for an extensive and Certified inspection every five years using a return form furnished by the same manufacturer, and to arrange for repair or extension of the lightning protection system whenever the system is affected by structural or roof alteration or repair to the building.
(Signed)
Owner or Designated Agent
Certified this day of , 19 at
City and State
MAIL ANNUAL MAINTENANCE FORMS TO:
(OWNER)
(ADDRESS)

FIGURE - 21

lightning protection components.

An LPI certified System has five other requirements: (7) adherence to NFPA Code No. 78; (8) conformance with UL Master Label Requirements, UL-96a; (9) installation supervision by a Certified Master Installer; (10) air terminals and conductors bearing UL parts labels and other parts conforming to LPI Material Specification; and (11) an annual inspection and maintenance agreement.

FIGURE - 22

Ben Franklin's legacy has not always moved smoothly through history. I'll list six common problems in their order of importance.

1. Religeous prejudices in the early days; the belief that ringing church bells would dispel the demons of the thunderstorms, or that prayer and ritual would do so.

2. The notion spread by rivals of Franklin that lightning rods would draw the thunderbolt and therefore "bring about the mischief they were meant to prevent".

3. Franklin himself was responsible for the idea that tall lightning rods would prevent lightning from striking. The lightning protection industry perpetuated the belief, claiming until 25 years ago that lightning protection bled off static charges but would intercept and ground any stroke that might occur. We now know that the latter purpose is the only important one.

4. Previously, "magnetic" and currently, "radioactive"

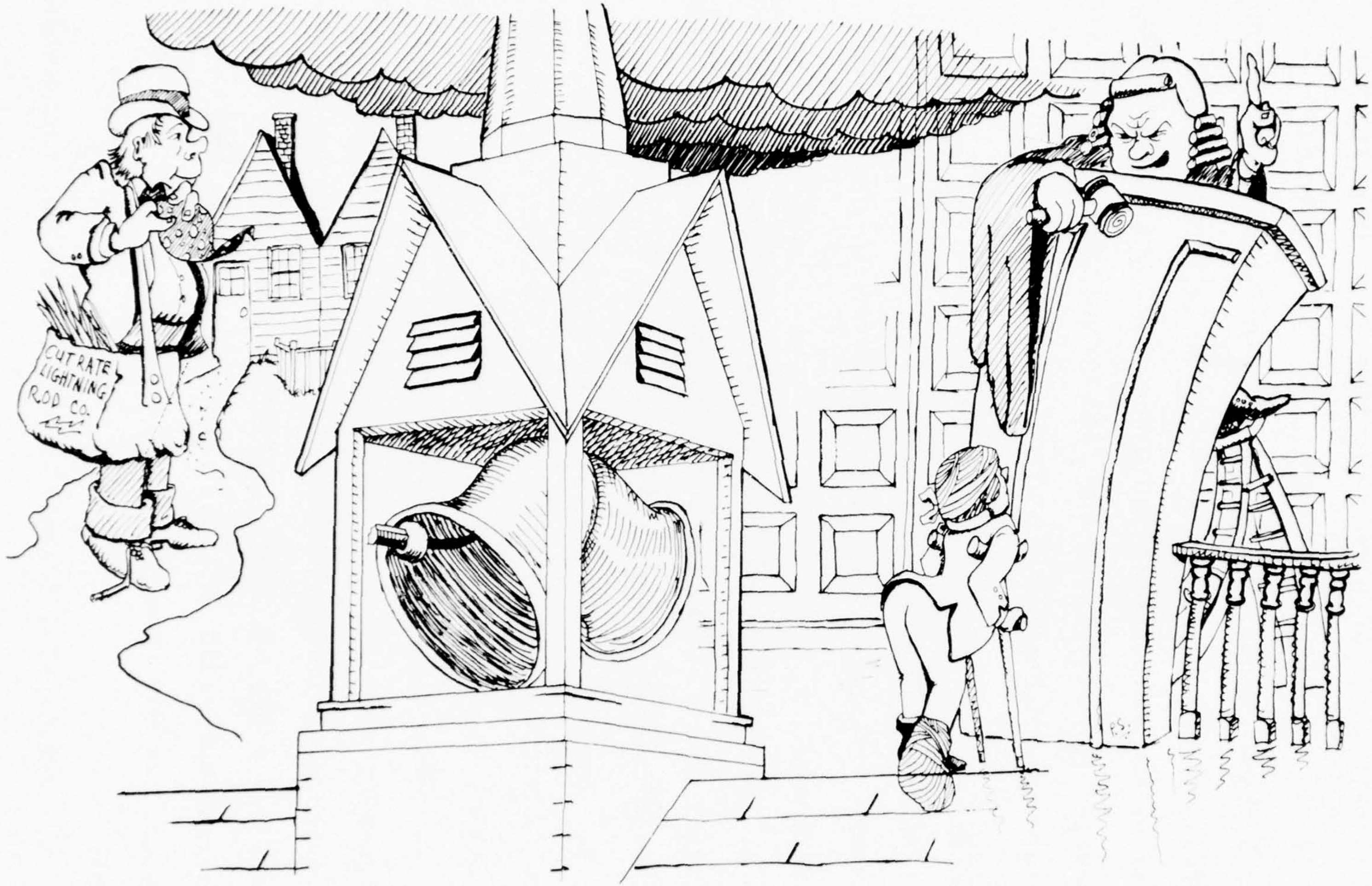


FIGURE - 22

lightning rods seem to persist no matter now many times leading authorities in Europe and America show theoretically and experimentally that the "power of the points" is sufficient; that the presence of radioactive materials does nothing to enhance the effectiveness of a lightning rod.

5. Countless deficient, un-inspected systems have been installed on a cut-rate price basis. Resulting failures have done an injustice to this industry.

6. Most persistent of all has been the "act of God" defense against lightning loss liability. Lightning is a natural phenomenon and is unpreventable. But defense against it is well-known, reliable, and inexpensive. Therefore, lightning safety is legally recognized today as the responsibility of man.

FIGURE - 23

Franklin was only human. On the plus side, he identified lightning as electricity, invented lightning protection, wrote the first specifications improving lightning rods, and produced several less well-known devices, among them the first thunderstorm warning device, a little bell outside his bed chamber that tinkled when a thundercloud passed overhead.

Three ideas that had less merit were a bed to be suspended by silken ropes in the middle of the room to insulate the sleeper from lightning; "Franklin Wires" for ladies' hats, which certainly would make their wearers more likely to be zapped by "step voltage"; and finally, the notion that a lightning rod

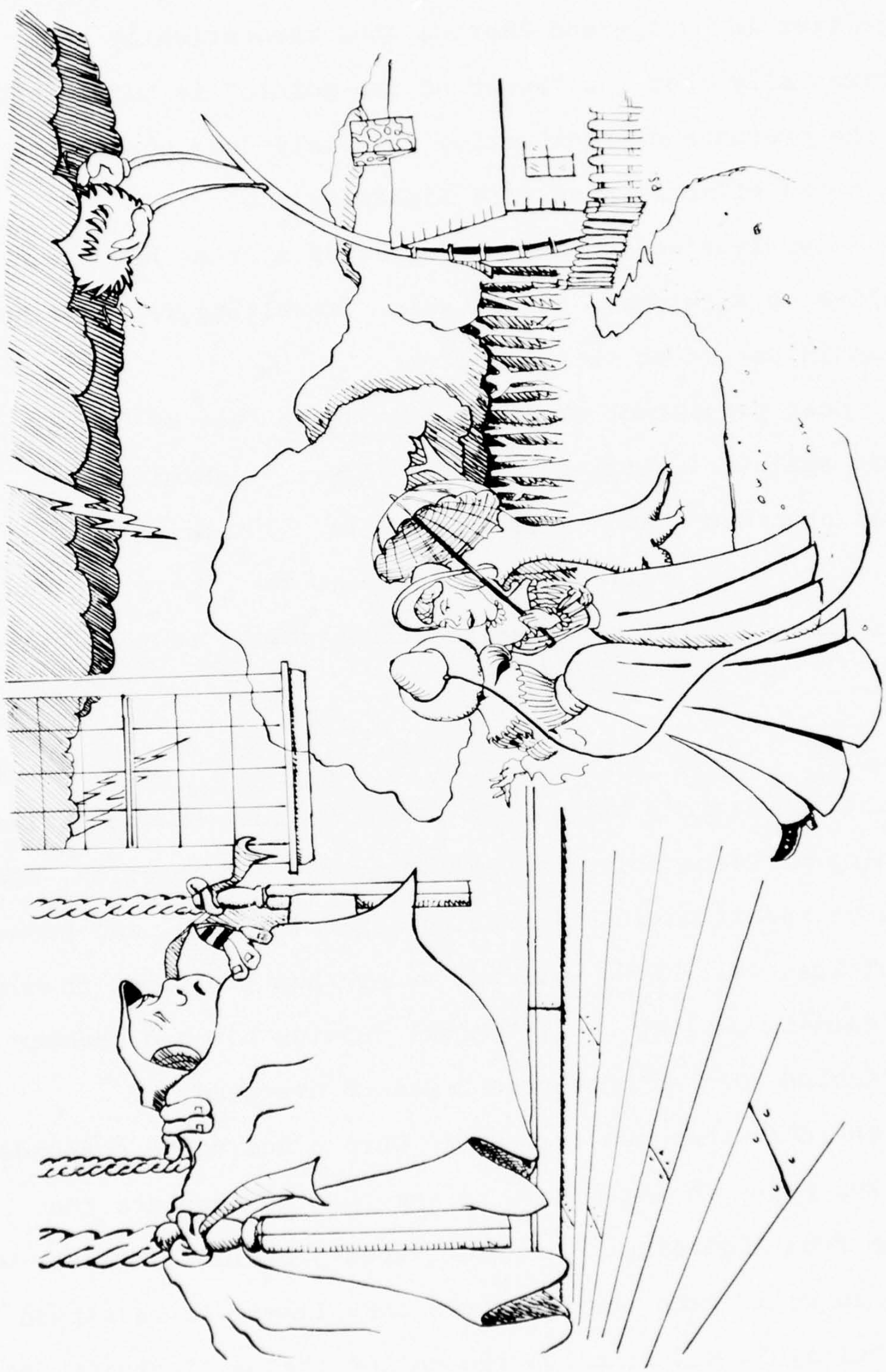


FIGURE - 23

would "silently draw electric fire from the cloud".

<u>FIGURE - 24</u>

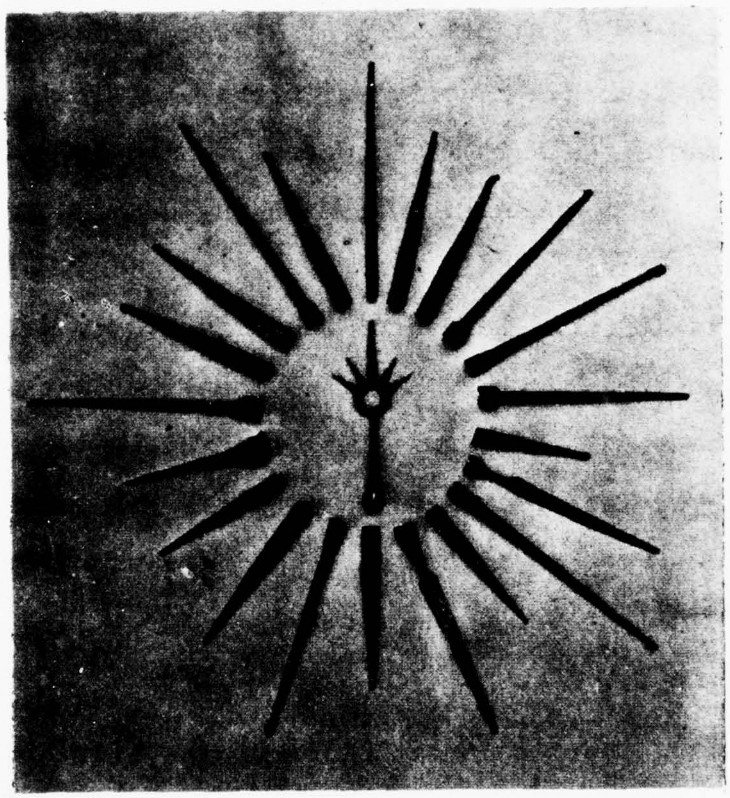
In 1772, Franklin wrote, "Pointed conductors....appear on private Houses in every Street of the principal Towns, besides those on Churches, public Buildings, Magazines of Powder, and Gentlemen's Seats in the Country....hitherto there has been no Instance of a House so guarded being damaged by Lightning; for wherever it has broken over any of them the Point has always receiv'd it & the Conductor has convey'd it safely into the Earth, of which we now have 5 authentick Instances".

Since then, thousands of protective instances have occurred. One Master Installer says he replaces points with melted tips almost every year on one set of single story buildings in an exposed, lightning-prone location.

<u>FIGURE - 25</u>

In 1974, during construction of the 1,824-foot high Dominion Tower at Toronto, a Canadian photographer, W. Hackle, made between 3,000 and 5,000 exposures and obtained six photographs of lightning striking air terminals.

The photo on the left shows a discharge to the copper air terminal at the end of a crane boom 85-ft. out over the project. The aircraft warning light at the end of the boom stayed lit. The air terminal was directly grounded to the lightning protection system by pure copper cable. So was the crane, yet in this case and later, the 135-foot, 18-ton grounded steel crane did not intercept the discharge. The air terminal did



These are old Lightning Rod Points that have been struck. They have saved buildings from destruction and persons from injury and death.

FIGURE - 24

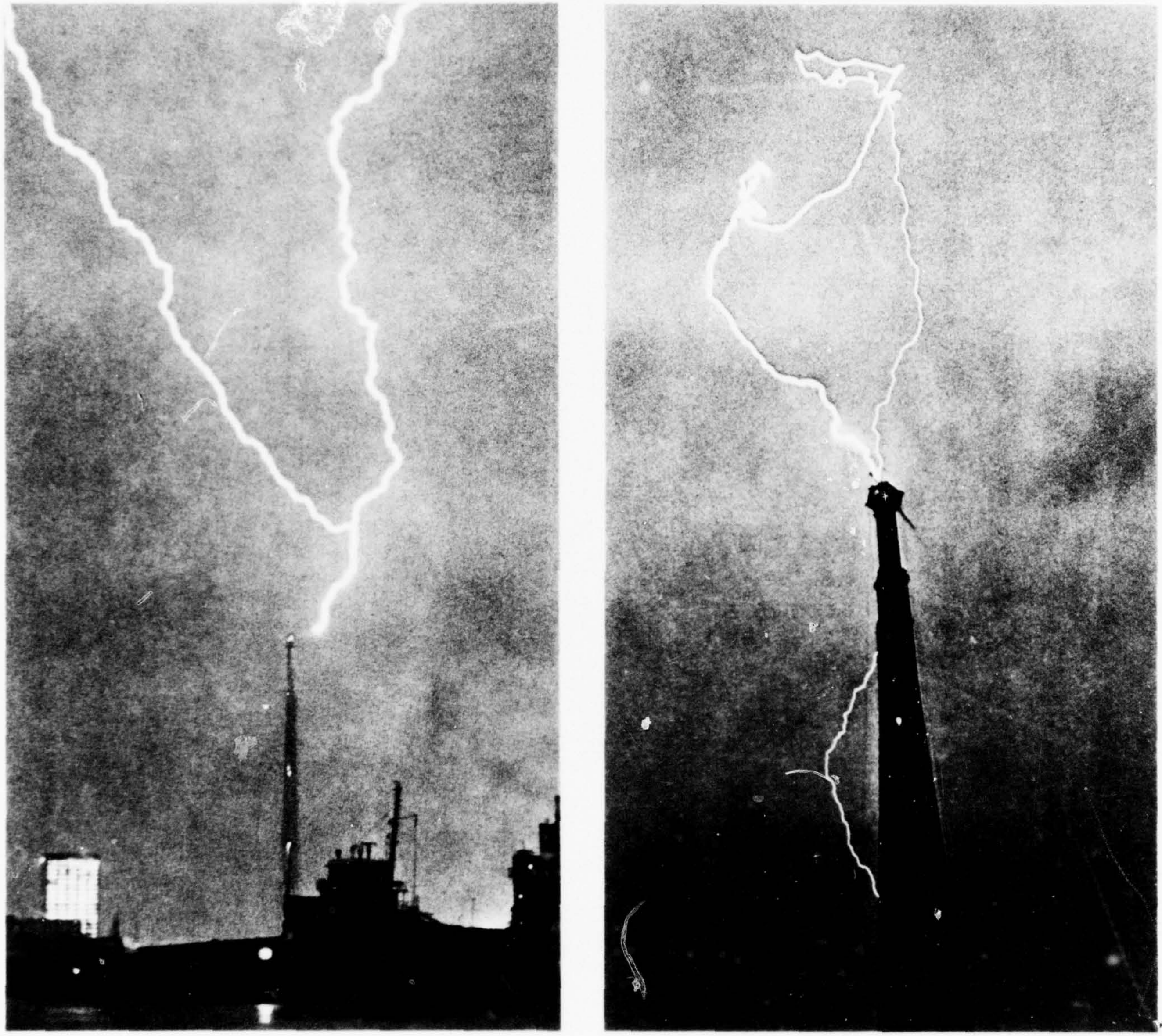


FIGURE - 25

so in each instance.

According to William A. Cliff, Field Engineer for Dominion Lightning Rod Co., Ltd., "These untouched photographs prove.... that air terminals together with a ground are 100 percent protection against lightning damage. Years of experience has proven that!"

Ben Franklin would have been pleased.

# # #

LIGHTNING PROTECTION

by

Dr. Rodney B. Bent

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Indian Harbour Beach, Florida

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

An understanding of the physics associated with lightning protection problems is presented in order that related design criteria will be better understood.

The mechanism of the lightning strike is related to protection problems on elevated structures of various heights, as well as overhead and buried cables. The risk of dangerous side-flashing, due to inductive loops when a grounding conductor is passing a steep waveform current is discussed, as well as the physical problems related to poor grounding, bonding and shielding.

The physical development of lightning induced line surges, and the magnitude of these surges on aerial and buried lines is explained. Finally, the properties of different basic types of suppression devices and the functions they perform is illustrated.

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1.0 INTRODUCTION

Correct information about the basic lightning process can lead to a much better understanding of lightning protection techniques and the resulting level of protection. The design of satisfactory lightning protection systems can therefore only be achieved with a knowledge of the mechanism and characteristics of a lightning strike and the related problems that a steep voltage wavefront has on inadequate bonding and grounding.

Lightning induced line surges can also cause major damage to electrical or electronic systems. A considerable proportion of the damage caused by such surges can be eliminated with careful planning of protection equipment.

This paper discusses all these points and attempts to educate the reader in some of the basic lightning protection problems. For more in depth information the reader is directed to several good publications on the topic.

2.0 THE LIGHTNING PROCESS IN A CLOUD-TO-GROUND DISCHARGE

A cloud-to-ground lightning discharge is made up of one or more intermittent partial discharges. The total discharge, whose time duration is of the order of 0.5 sec, is called a flash; each component discharge, whose luminous phase is measured in tenths of milliseconds, is called a stroke. There are usually three or four strokes per flash, the strokes being separated by tens of milliseconds. Often lightning as observed by the eye appears to flicker. In these cases the eye distinguishes the individual strokes which make up a flash. Each lightning stroke begins with a weakly luminous predischarge, the leader process, which propagates from cloud-to-ground and which is followed immediately by a very luminous return stroke which propagates from ground-to-cloud.

It has been found that the electrostatic field takes about 7 sec to recover to its pre-discharge value after the occurrence of a lightning flash at a distance beyond 5 km, but when the flash is very near the recovery time may be different due to the presence of space charge. In both cases, regeneration of the field takes place exponentially.

2.1 Stepped Leader

The usual cloud-to-ground discharge probably begins as a local discharge between the p-charge region in the cloud base and the N-charge region above it (Fig. 1). This discharge frees electrons in the N-region previously immobilized by attachment to water or ice particles. The free electrons overrun the p-region, neutralizing its small positive charge, and then continue their trip toward ground, which takes about 20 msec. The vehicle for moving the negative charge to earth is the stepped leader which moves from cloud-to-ground in rapid luminous steps about 50 m long. In Figures 1 and 2 the luminous steps appear as darkened tips on the less luminous leader channel which extends upward into the cloud. Each leader step occurs in less than a microsecond. The time between steps is about 50 μ sec.

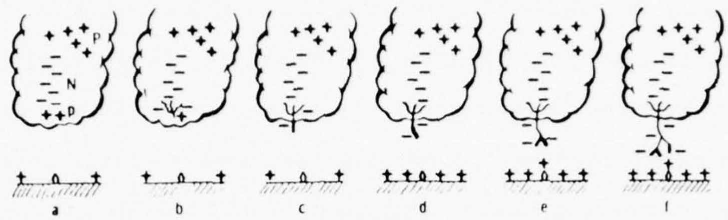


Fig. 1. Stepped leader initiation and propagation. (a) Cloud charge distribution just prior to p-N discharge. (b) p-N discharge. (c)-(f) Stepped leader moving toward ground in 50-yard steps. Time between steps is about 50 millionths of a second. Scale of drawing is distorted for illustrative purposes. (from Uman(6))

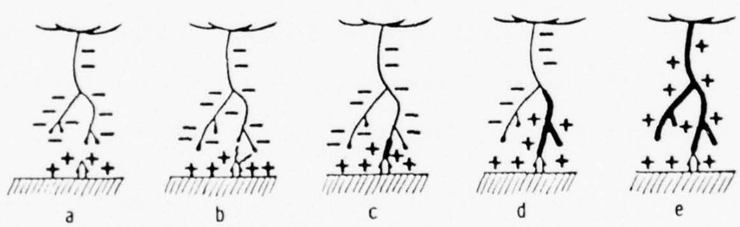


Fig. 2. Return stroke initiation and propagation. (a) Final stages of stepped leader descent. (b) Initiation of upward-moving discharges to meet downward-moving leader. (c)-(e) Return stroke propagation from ground to cloud. Return stroke propagation time is about 100 millionths of a second; propagation is continuous. Scale of drawing is distorted. (from Uman(6))

2.2 Return Stroke

When the stepped leader is near ground, its relatively large negative charge induces large amounts of positive charge on the earth beneath it and especially on objects projecting above the earth's surface (Fig. 2). Since opposite charges attract each other, the large positive charge attempts to join the large negative charge, and in doing so initiates upward-going discharges. One of these upward-going discharges contacts the downward-moving leader and thereby determines the lightning strike point. When the leader is attached to ground, negative charges at the bottom of the channel move violently to ground, causing large currents to flow at ground and causing the channel near ground to become very luminous. The channel luminosity propagates continuously up the channel and out the channel branches at a velocity somewhere between 1/2 and 1/10 the speed of light. The trip between ground and cloud takes about 100 μ sec. When the leader initially touches ground, electrons flow to ground from the channel base and as the return stroke moves upward, large numbers of electrons flow at greater and greater heights. Electrons at all points in the channel always move downward even though the region of high current and high luminosity moves upward.

It is the return stroke that produces the bright visible channel. The eye is not fast enough to resolve the propagation of the return stroke, or the stepped leader preceding it, and it seems as if all points on the channel become bright simultaneously. A unique video photograph of the lightning leader with the return stroke partway up a double channel is shown in Figure 3.

2.3 Lightning Current

A full understanding of the time variation of a lightning current can only be obtained by oscillograph recording of the object struck. Because of the rare occurrence of lightning to an object of normal height, it is very unlikely that good statistics can be obtained without great expense

Fig. 3 Leader and first return stroke of a multiple (6) return stroke flash of forked lightning.

and observations over a considerable period of time. Lightning currents therefore, are mostly measured on tall structures or balloons connected to earth with steel cables. The currents from lightning have been found to be unidirectional and primarily discharge negative currents. Figure 4 shows a frequency-distribution curve of lightning current amplitudes, incorporating the best information available.

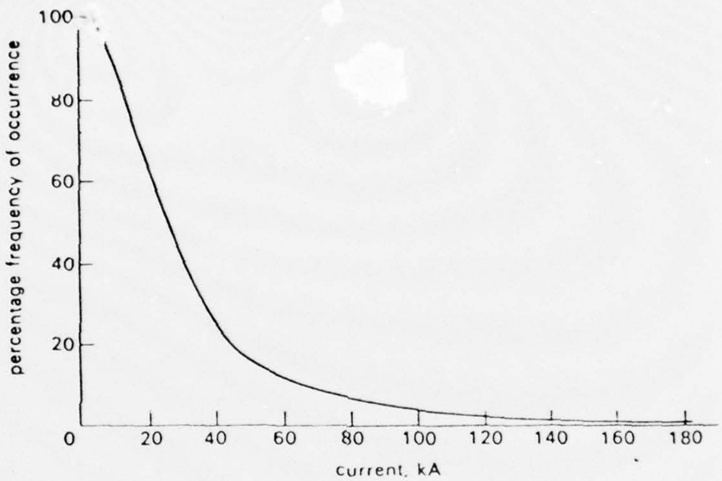


Fig. 4 Frequency distribution of lightning current amplitudes

The maximum value reliably recorded is 340k amps, but much higher amplitudes cannot be ruled out. The highest values occur primarily with the rare positive strokes.

A significant characteristic for lightning protection is the rate of rise of the current waveform. It has been generally assumed in the recent past that the lightning current waveform reaches a peak in some 1 to 3 μ sec. More recent information by Llewellyn[1] in 1977 indicates that the current risetime may be much less than 1 μ sec. Figure 5 shows some risetimes for a selection of close and distant storms. For some storms the average time to peak value was found to be of the order of 1/4 μsec. The effect of this term on lightning protection will be discussed later.

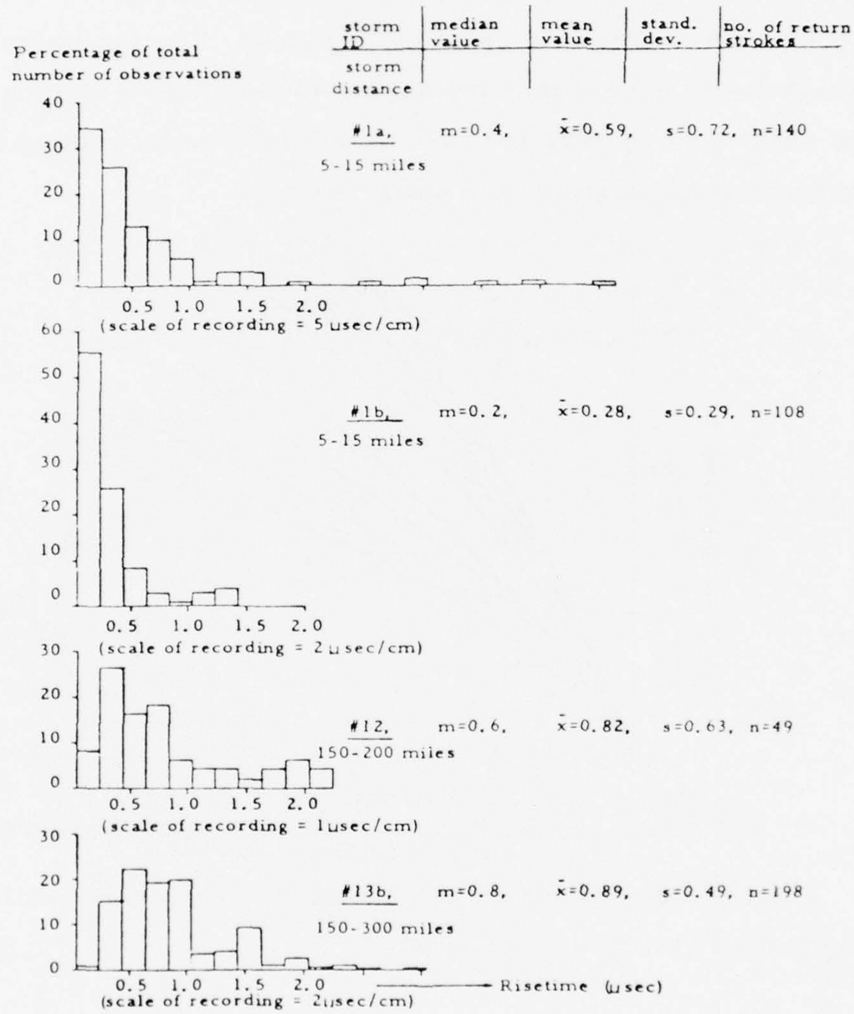


Fig. 5 Histograms of Risetimes of the Return Stroke Magnetic Waveforms for the Individual Storms.

2.4 Breakdown Voltage

Breakdown tests of long spark gaps are made with impulse generators of 5 million volts or more where the test voltage rises at rates between 60 and 600 kV/μsec. Most of these tests are concerned with sparkover under a positive switching impulse because they produce much lower breakdown voltages than negative impulses. The minimum breakdown voltage is of concern to many engineers and Figure 6 gives representative test results by showing the variation of breakdown voltage for different electrode configurations and polarities.

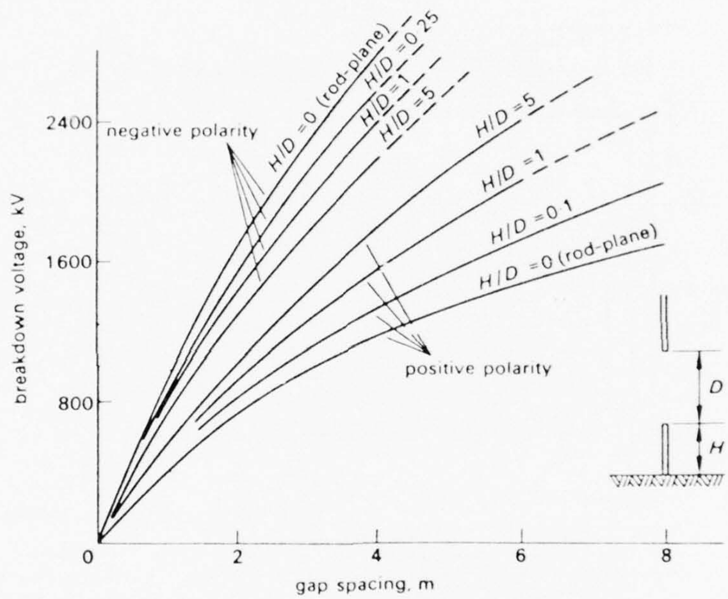


Fig. 6 Switching-impulse breakdown voltage of rod–rod and rod–plane gaps (Anderson and Tangen, 1968) (2)

Further information on breakdown voltages are given in the book "Lightning Protection" by Golde.(3)

2.5 Striking Distance

A normal negative leader progresses to earth in discrete steps until a counter streamer is initiated from ground or a grounded object. It is therefore at that particular distance that the point of strike is determined. This striking distance is defined as that distance between the tip of the

lightning leader and the point to be struck. The main interest is limited to structures up to about 20 m height; structures of greater height begin to require special consideration as their height is greater than a leader step, and they may also induce upward going leaders. It is assumed after looking at Figure 6 that the critical breakdown between the tip of the lightning channel and earth is of the order of 5 kV/cm for a normal negative stroke and 3k V/cm for the rare positive stroke. Small changes in this critical breakdown voltage gradient have little effect on the resulting value of the striking distance which is shown in Figure 7.

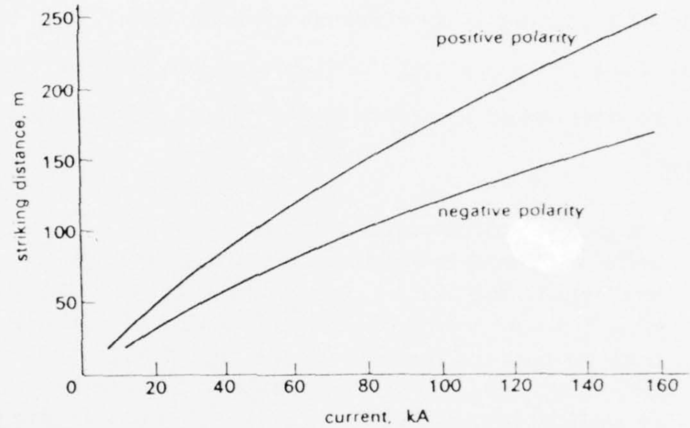


Fig. 7 Variation of striking distance with lightning current amplitude

The important conclusions from these results are that striking distance increases with the severity of the discharge; for an average 25 k amp strike the distance is about 40 m. More important, however, these results and associated theory show that the progression of the leader remains quite unaffected by any feature on, or below ground, until the tip of the leader has reached a height of only a few tens or, at most, two hundred meters above ground. These results therefore provide quantitative evidence against the belief in lightning concentration areas.

3.0 THE LIGHTNING ROD AND ITS CONDUCTORS

3.1 The Lightning Rod

It is a common misconception that lightning rods discharge clouds and thus prevent lightning. The rod only serves as a means to route the lightning harmlessly to ground by diverting the lightning when it approaches the striking distance discussed in the previous section. In the two hundred years since Benjamin Franklin investigated lightning many manufacturers have tried to influence the public in the dissipation principle of lightning protection or elimination. This technique most certainly does not work and the lightning physicists' thoughts on this subject are discussed in masterly fashion by Golde in the following statement:

> "It is a manifestation of human weakness that a prejudice once acquired tends to be retained even in the face of overwhelming factual evidence contradicting the basis on which it was founded. In the realm of science a prejudice may be termed a misconception. Such a misconception which has persisted for over two hundred years and which is still widespread is the belief that a lightning conductor has the ability, or indeed the purpose, of dissipating silently the electric charge in a thundercloud thus preventing the "protected" building being struck".

There are several manufacturers of either radioactive lightning rods or lightning dissipation systems. The predominant scientific belief, however, is that neither of these systems are any benefit over the conventional lightning protection system. There do seem to be some satisfied customers however, for the dissipation arrays and a U.S. Navy report[4] and FAA report[5] discuss both sides of the topic.

The lightning rod has the purpose of intercepting a lightning strike and deflecting it from the structure. When several lightning rods are to be put on a building one should develop a common-sense solution which will strike a reasonable balance between protection and cost.

It is possible, with care, to use existing gutter and rain pipes to obtain protection at reduced costs, but care must be taken when incorporating modern metalic roofing materials to be part of the system. Lightning can penetrate metal sheets of 1mm thickness or more, and perhaps the cost of such repair might be acceptable. The minimum thickness is defined in certain codes to be 0.3mm for copper, and 0.5 mm for other metals. Some roofs use metal foils of less thickness. A lightning strike to this type of roof will not only burn a large hole but can cause large areas of foil to be torn off due to the mechanical effects.

3.2 Down Conductors

When lightning strikes an air terminal the injected current must be transferred by the shortest possible path to ground. The down conductor has this function, but because the inductance of this down conductor is a major factor in determining the occurrence of the dangerous side-flash to some internal grounded object, it must also have the lowest impedance that can be afforded.

The inductance of a down conductor is directly proportional to its height. By paralleling two down conductors their combined inductance is reduced to approximately one-half that of a single conductor and so on. The down conductors should not be spaced too close together however, otherwise the above rule is not accurate. The importance of having at least two down conductors is therefore a considerable advantage in reducing the dangerous side-flash, the action of which is discussed later. Right angle bends in a down conductor also increases the inductance and such a design needs careful consideration.

Once a lightning strike has been intercepted and passed to the surface of the earth, it is the function of earth electrodes to discharge the current into the ground. Two important factors are the ground resistance, which plays a part in side-flashing, and the potential distribution over the ground

surface. If the ground resistivity is high advantages can be achieved by bonding the down conductors to water pipes to lower the resistance to ground. The risk in side-flashing is thus determined exclusively by the inductance.

Side-flashing can also occur below the ground to buried metal pipes or wires and care must be taken in the design and positioning of the grounding electrodes. Typical values of impulse breakdown in soil are 2 to 5kV/cm, which leads to side-flashes of several meters. In air the value is 9kV/cm and brick and concrete has a slightly lower breakdown strength.

It is interesting to note that the length of a ground rod has a much more significant effect on the resistance than its radius. Curves demonstrating this effect are shown in Figure 8, which also implies that little benefit is achieved by extending the rod beyond 2 or 3 meters or increasing its diameter beyond 1.25 cm. Strip electrodes are beneficial where high resistivity ground exists below a layer of low resistivity.

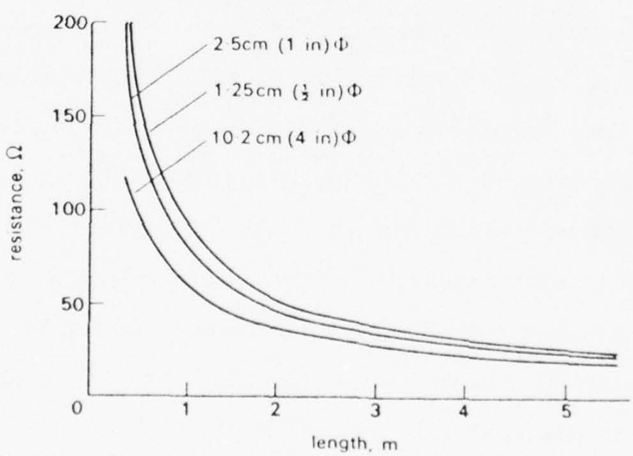


Fig. 8 Variation of earthing resistance of rod electrodes of different diameter with length (British Code 'Earthing')

3.3 Materials

The type of material used for roof and down conductors seems to be governed by tradition. Copper, aluminum and galvanized steel are all acceptable but there are conflicting opinions as to whether the material should be of rod, tube, strip or stranded form. Stranded copper is not deemed acceptable in the codes of several countries, although it is accepted in the USA code. Copper or copper alloys must not be used on a building with aluminum fillings.

A strong corrosive effect can be caused by rainwater dripping off copper conductors onto some metals such as zinc or lead which are often used on buildings. Dissimilar metals should be avoided as far as possible and one should be aware that stranded materials are more severely attacked by corrosion than solid conductors.

Corrosion plays a high risk underground, in particular to aluminum which is totally unacceptable. The electrolytic properties of some soils cause corrosion to all these metals, as do stray currents produced by DC railway lines on DC high voltage systems where the earth is used as a return path. Cathodic protection can help eliminate this type of problem.

4.0 ELECTRICAL, MECHANICAL AND THERMAL EFFECTS

4.1 Electrical Effects

No lightning strike to a structure has attracted more attention in the last decades than the so-called side-flash. It has been examined repeatedly and its dangers are illustrated in the technical literature. Its prevention must be provided in order to stop incidents in which a protected building has been struck and a person in such a building injured.

Golde has illustrated the principles of the conditions leading to the risk of a side-flash with the simple example shown in Figure 9.

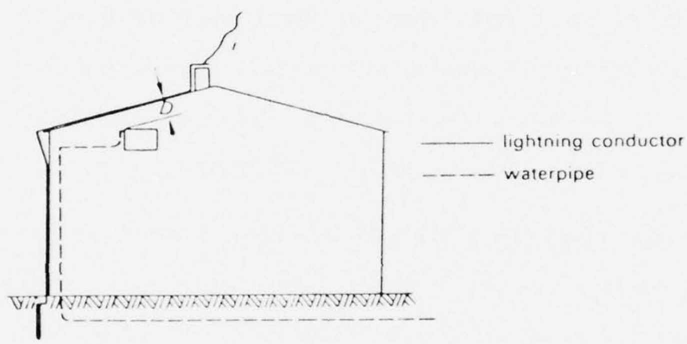


Fig. 9 Lightning strike to house and lightning conductor and independently earthed water system

The illustration shows the outlines of a domestic building with a lightning conductor protecting the chimney which constitutes the highest point. In the attic is a water tank which is fed through a metallic water pipe which, in turn, is connected to a metallic main buried in the ground.

Let us now assume that the lightning conductor on the chimney is struck by a lightning current of amplitude i. The current is then discharged along the roof conductor, the single down conductor and into the earth electrode. This path constitutes an inductance L while the impedance of the earth electrode may be described by its effective ground resistance R. The top of the lightning-protective system is thus raised to a potential with respect to true earth which is given by:

$$u = iR + L\,di/dt$$

For the purpose of a numerical estimate we may assume an intense lightning current of crest value i = 100 k amp and a ground resistance of R=10 Ω. The inductance of a single vertical conductor is about 160 μH per 100 m and the rate of rise of the front of the lightning current may be taken as 50 kamp/μsec. If the height of the chimney above ground is 10m, the top of the lightning conductor is raised to a potential with respect to true earth which amounts to:

$$u = 10^5 \times 10 + 10^{-1} \times 1.6 \times 10^{-4} \times 5 \times 10^4 \times 10^6 \text{ V}$$
$$= 10^6 + 8 \times 10^5 \text{ V} = 1.8 \text{ MV neglecting phase differences.}$$

In contrast, the water tank remains at ground potential even when the house is struck so that the potential difference of 1.8 MV is suddenly impressed between the lightning-conductor system and the water tank. If the electric breakdown strength of the clearance D is less than that potential difference an electric breakdown occurs from the lightning conductor to the water tank; and this is termed a side-flash. The breakdown strength of air for a chopped impulse voltage can be taken as 900 kV/m, hence a 2m flash could materalize. Similar situations may occur if people are standing between a grounded air-terminal lead and a grounded instrument in the building. Side-flashes may also occur under the surface and in the process can throw up rocks and soil over great distances. The simple solution of bonding the down conductor to the grounded object will alleviate many problems.

4.2 Thermal Considerations

The lightning leader stroke has a narrow cone which is surrounded by much larger corona. The return stroke current is concentrated in this central cone which is about 1-2 centimeters diameter and a maximum temperature of about 60,000 °F is reached after a few microseconds, as shown in Figure 10.

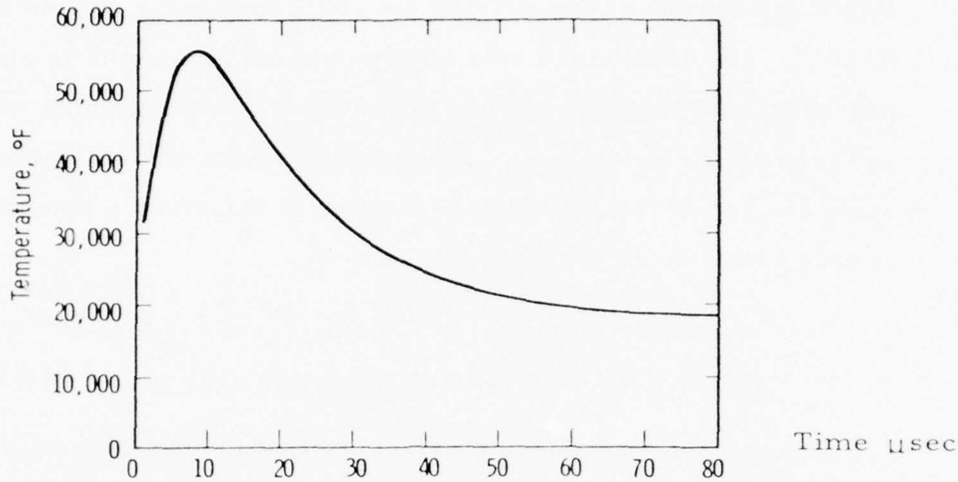


Figure 10. Temperature-time curve for return stroke. (Uman[(6)])

The effects of this temperature on metals is usually not serious, although there is a possibility that a thin metal sheet will be penetrated. The temperature rise is proportional to i^2t where a maximum value of $\int i^2 t\, dt$ is about 10^7 amp^2 sec. Neglecting dissipation and referring to Figure 11 one sees that the temperature rise of copper conductors as specified in most lightning codes as 30 to 50 mm^2 is moderate. For aluminum the temperature values can be taken as 1.5 times those for copper.

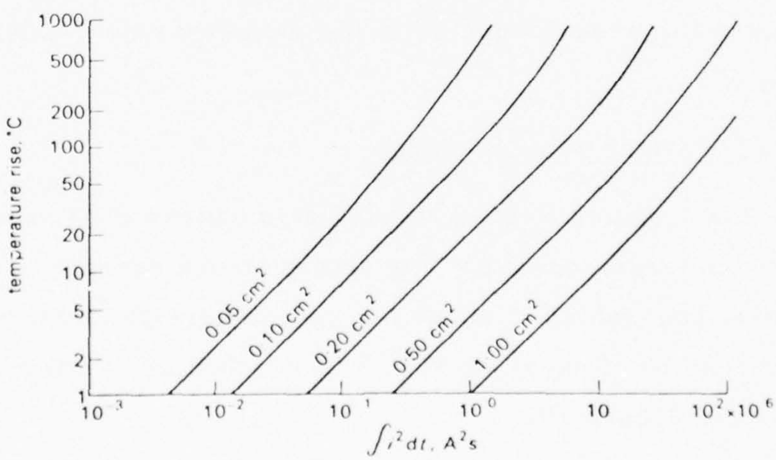


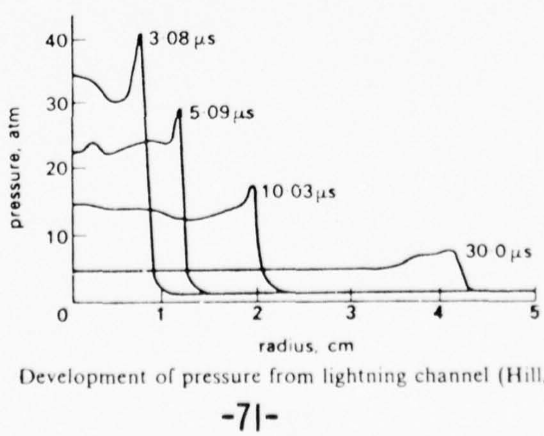
Fig. 11 Temperature rise in copper conductors of varying cross section as function of $\int i^2\, dt$

There is one aspect of heat dissipation that needs consideration. Where the lightning current is being discharged through a high resistance joint, such as a poor contact or overlapping metal sheets, the heat generated may give rise to heavy sparking. Penetration may occur in the case of thin metal sheets such as used as roofing material or air-craft skin. The size of the hole is a function of lightning charge, the material and its thickness. For 20 mil copper the hole could be up to 300 mm^2.

When lightning strikes an insulating material the point of contact could be raised to a high temperature and penetration could result. By these means clean holes of 2 cm diameter have been punched in glass by lightning discharges. If this insulant contains moisture the current will flow preferentially along the path of best conductivity. Moisture can be converted into steam and explosions occur. Enormous blocks of concrete have been demolished this way and on one occasion rocky ground was furrowed for 800 feet and 75 tons of rock and soil dislodged. The explosive effect was equivalent to 600 lbs of TNT.

4.3 Mechanical Considerations

Mechanical effects concern the shock wave and bending forces. With the rapid temperature increases discussed in Section 4.2 the air surrounding the channel expands extremely rapidly and produces a super-sonic pressure wave. Figure 12 shows how this wave is propagated from the central cone. It is responsible not only for thunder, but also for widespread lifting of tiles on the roofs of buildings.



(7)

Fig. 12 Development of pressure from lightning channel (Hill, 1972)

Two parallel conductors caught in a lightning discharge are subject to attractive forces and these forces are responsible for the fusing of stranded conductors and for squashing hollow conductors.

There is one more mechanical force worth considering. If a lightning conductor follows a right-angle bend on a building and this conductor has to discharge a lightning current, it will be subject to a mechanical force trying to straighten it and thus attempting to bend it outward. The magnitude of the force is proportional to the square of the current, but even for large strokes it can only reach about 5000 lbs. Sharp rectangular bends in conductors should therefore be avoided.

5.0 LIGHTNING SURGES

The major sources of lightning surges in conductors are due to

a) Ground potentials caused by nearby lightning strokes

b) Induced effects caused by lightning current flowing on a shield

c) Direct strikes to a wire

d) Side-flashes to the conductor from a nearby strike

e) A straight conductor acting as an electric field change antenna for lightning effects

f) A looped conductor acting as a magnetic field antenna for lightning effects.

Burying the cable does not remove lightning effects as the cable is then an ideal ground path for the current. The lightning current may side-flash several meters to the conductor under the ground, where the distance is primarily a function of solid resistivity and the resistance of the conductor to ground.

The largest lightning voltage recorded on a transmission line reached a peak value of 5 million volts in less than two microseconds. The resulting oscilloscope recording is shown in Figure 13 and the strike occurred some 4 miles up the line. It is suggested that closer to the strike

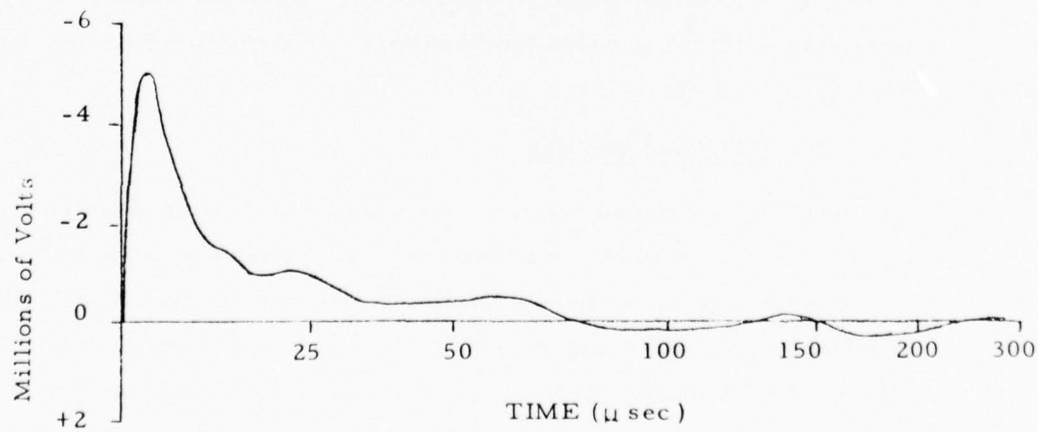


Figure 13. Cathode-ray oscillogram of highest voltage on a transmission line; 110 kV wood pole of Arkansas Power and Light Company; no ground wire.

point the current rate of rise was probably of the order of 10 million volts per microsecond.

Residential 120 VAC lines are found to experience peak lightning associated voltages of up to 6kV and internal switching transients up to 3kV. The transients will be oscillatory in nature with a fundamental frequency from a few tens of kilohertz to several megahertz with components ranging into hundreds of megahertz. They will last from 100 nanoseconds to 100 microseconds and be clamped within a few cycles. Good grounding and bonding may reduce the transients significantly.

5.1 Insulation Effects

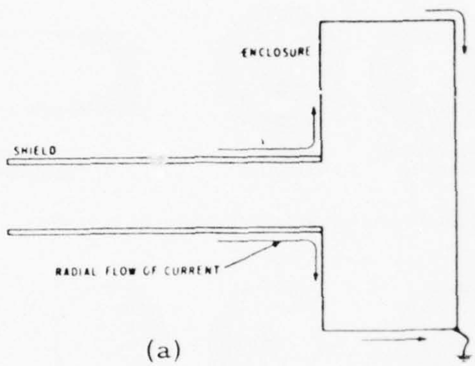
The effect of high voltages on insulation can be quite large and whereas the initial breakdown of an insulator may not be catastrophic, the repetitive effects of high voltage transients will produce breakdown at the same place until the insulator cannot even stand the steady state voltage. An electric clock manufacturer reduced his failure rate to one hundredth of his earlier failure rate by increasing the insulation level from 2 to 6kV.

Breakdown will also occur along a surface such as a printed circuit board. In this case, a path of slightly conductive carbonized insulation will occur which may also be influenced by vaporized metal. Steep wavefront voltages may lead to breakdown of insulation between the windings of a coil.

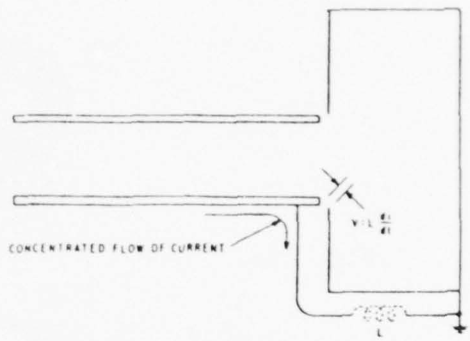
5.2 Grounding and Bonding

When one grounded conductor is conducting a steep wavefront current large potentials may develop between it and another grounded object. The effects of this problem have been illustrated and discussed in Section 4.1. Bonding the grounds together would have removed the problem. The inductive effects of such bonding between two objects must be carried out with care or it may still lead to hazardous potential differences. This problem is

illustrated in Figure 14 where a cable shield and an enclosure are connected together (reference 8). This example indicates that ground leads should be kept as short and direct as possible. Figure 14a shows a shield being terminated on an enclosure which allows the current to flow radially from the shield to the enclosure. If a separate ground lead is used to carry surge current it will have an inductance (Fig. 14b) which



(a)



(b)

Figure 14. Connections between shield and enclosure. (a) Good. (b) Bad.

will lead to a potential difference between shield and enclosure. The inductance of one inch of 0.034" diameter wire is about 0.0134 μh and with a rapid current pulse of 100 amp/nsec the voltage developed will be 1340 volts. Ten inches of wire will enable 13kV to develop between shield and enclosure, implying a spark over 1 cm long. The wire should, therefore, be kept as short as possible.

It is also absolutely essential that a shield be grounded at both ends. The magnetic fields caused by lightning can induce voltages around open circuit loops and currents around short circuit loops. The induced currents hardly ever cause damage, but the induced voltages can be excessively high and will cause damage.

Ideally one must set up separate grounding systems for the various electrical parts of a system and combine these separate grounds at only one common reference point.

5.3 Skin Effect

Skin effect is a phenomenon which tends to concentrate currents on conductor surfaces that are nearest to the field sources producing these currents. An example of current distribution in conductors because of the skin effect is described by Everett in reference 9 and an illustration is given in Figure 15. It can be seen that most of the current tends to

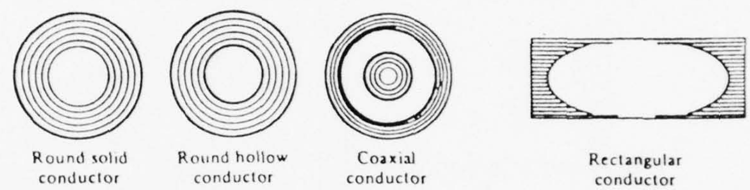


Fig. 15a. Current distribution in conductors because of skin effect.

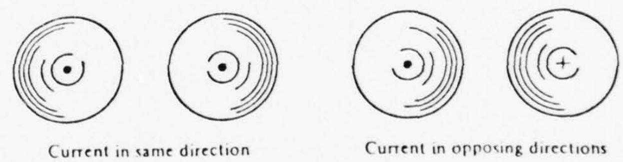


Fig. 15b. Proximity effect of current in parallel wires.

flow in a thin shell near the conductor surface where the depth of penetration is a function of resistivity and frequency. The connection of grounds to the inside of conducting structures may therefore not always be advisable as current will then tend to flow on the inside surface.

6.0 PROTECTOR DEVICES

Protector devices are of two basic types, constant voltage and crowbar. The constant voltage devices will conduct very little at the steady state voltage, but above a certain voltage level will conduct very heavily. A crowbar device in effect, short circuits a high voltage to ground. This short will continue until the current is brought to a low level. A constant voltage unit will never reduce the line voltage below its steady state value but the crowbar device often will. This could be a problem if there is a continuing follow current.

Constant voltage devices in everyday use are avalanche and zener diodes and varistors, or voltage dependant resistors. Spark gaps and gas discharge tubes are the most common type of crowbar.

Low pass filters are often used as suppression devices. A capacitor placed across the terminals is the simplest form of filter where the impedance it should present to the transient will be much lower than the transient source impedance. This approach will work well unless the capacitor loads down the desired voltage and does not create current in-rush problems. A resistor in series will help but will reduce the effectiveness of the filter. A capacitor network is also ineffective if the transient has high energy in either polarity. Filters can become expensive and must be very carefully designed.

The lead length of suppression devices can cause large overshoot voltages depending on the rate of rise of current. It was discussed in Section 5.2 that a one inch wire can lead to a voltage overshoot of over 1300 volts. It is possible, however, to purchase most protection devices in disc form without wires,and with careful mounting the voltage overshoot will be negligible.

6.1 Avalanche Diodes and Zeners

The volt-ampere characteristics of a semiconductor diode are shown in Figure 16 in which there are three principle regions of

operation. The forward biased region is limited by the external circuit and the leakage region is where the voltage is reversed but is still less than the critical value. When the reverse voltage increases beyond this

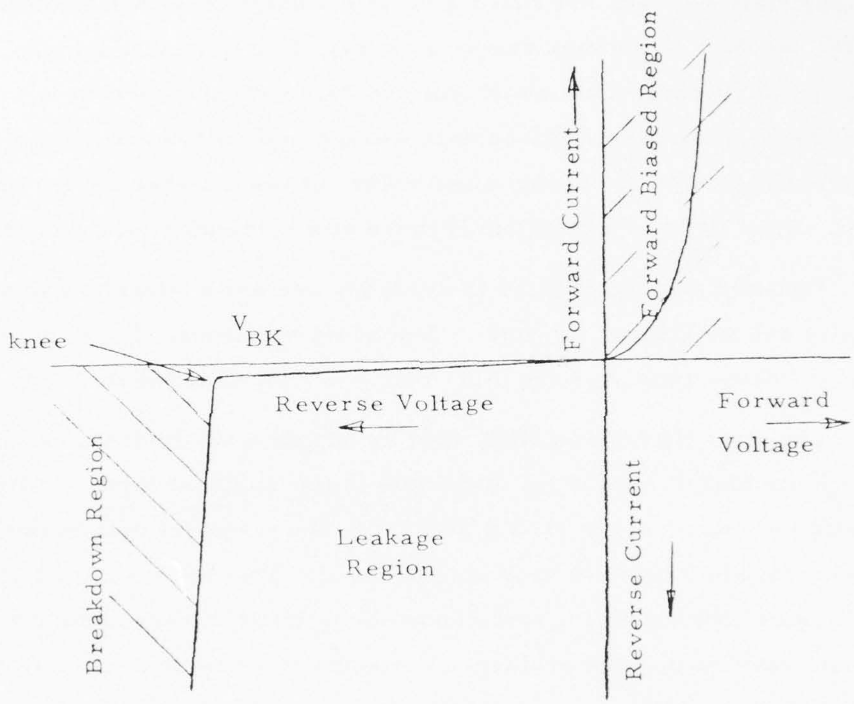


Figure 16. Schematic volt-ampere characteristic curve for a semiconductor diode.

critical value the reverse current increases sharply and the diode is operating in the breakdown region. Normal rectifier diodes are made to operate in the forward and reverse-biased region, but transient suppressors operate around the breakdown region.

Avalanche diodes exhibit a sharp turn at the knee, but zener diodes go through this transition more gradually. This implies that the avalanche diode is a better suppressor for transients than zener diodes.

These devices are the most "constant voltage" devices available and the voltage is only slightly dependent on the current. The operation takes place within a very small volume of silicon, where the energy or heat generated by the transient can cause failure at the junction. Special suppression devices using the silicon avalanche technique are manufactured that have a junction area ten times larger than a one watt zener diode; the Tranzorb made by General Semiconductor Industries is one such device. These devices will clamp at speeds in excess of 10^{-12} sec and, depending on the size, the peak power rating can be up to several hundred kV for a 1 μsec pulse. They do have a small capacitance, however, but with careful design it is possible to use them in protection circuits at frequencies in excess of 100 MHz.

6.2 Varistors-Voltage Dependent Resistors

A varistor is a bulk semiconductor device whose resistance varies with the magnitude but not the polarity of the applied voltage. Varistors are composed of a polycrystalline material made by pressing and heating special mixtures containing either silicon carbide (SiC) or oxides of zinc and bismuth. Metal-oxide varistors (MOV's) have a more nonlinear V-I relationship and therefore better clamping. They are highly nonlinear elements developed recently for protection of electric devices from induced voltage surge. In the absence of abnormal voltage, the MOV presents a very high resistance at its terminals; however, in the presence of a surge, its resistance diminishes by several orders of magnitude, thus absorbing the energy of the transient above a specified value.

MOV's provide low voltage nonlinear elements with voltage-current characteristics comparable to zener diodes, but with a bi-polar property and high energy dissipation/size capability. These devices, primarily intended for surge protection of AC power lines, will be also applicable to low voltage signal line protection when lower voltage types of MOV become available. The step response of an MOV is in the nanosecond range. Typical V-I curves are shown in Figure 17.

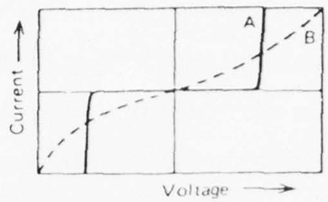


Figure 17a. Bilateral and symmetrical V-I curve, A:MOV, B:SiC varistor.

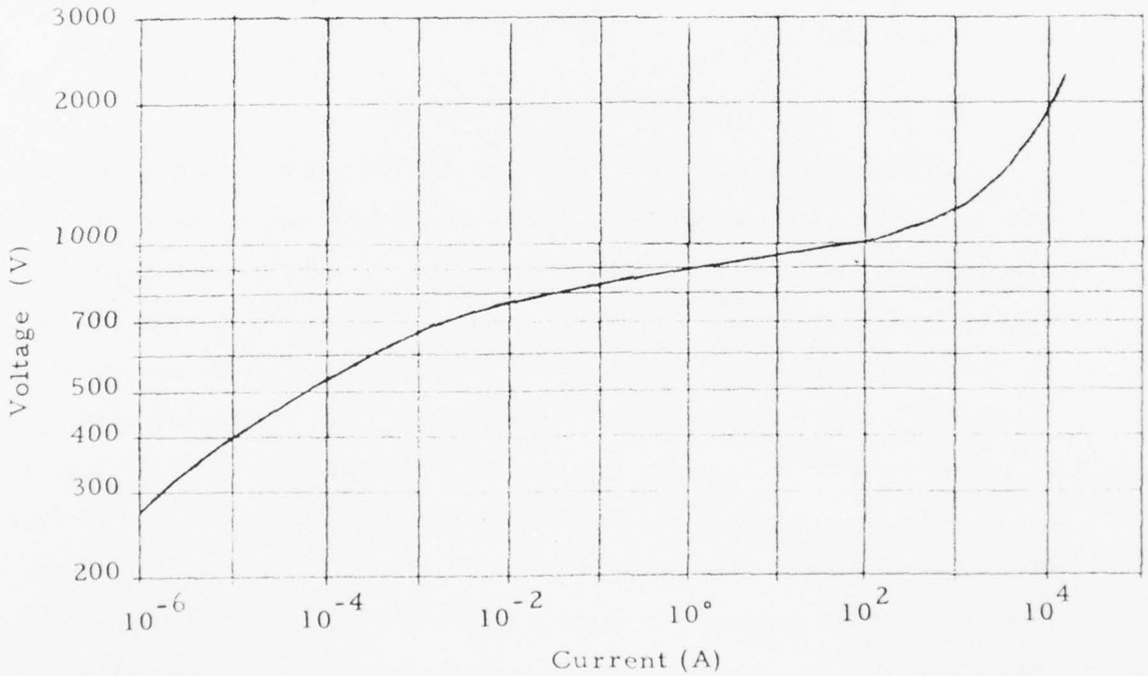


Figure 17b. V-I Curve for ERZ-C32 EK621 (Panasonic)

6.3 Gas Breakdown Devices

On the opposite end of the ruggedness spectrum are the spark gaps and gas-discharge tubes (GDT's). These depend on the formation of an ionized gas between metal electrodes. The gap length, gas pressure, and several other factors determine the breakdown voltage. When an arc is formed, the suppressor is capable of conducting high currents at a low voltage ($\lesssim$ 100V).

Unfortunately, the steady state power source is frequently capable of keeping the arc conducting until current and voltage are reduced, temporarily disabling the supply. Many such suppressors also have a noticeable response time, such that a fast-rising transient reaches a high voltage before the arc can form. GDT's are not generally feasible below 90 volts.

Druyvesteyn and Penning[10] describe the action of a gas discharge device in Figure 18, where one can see the important glow and arc

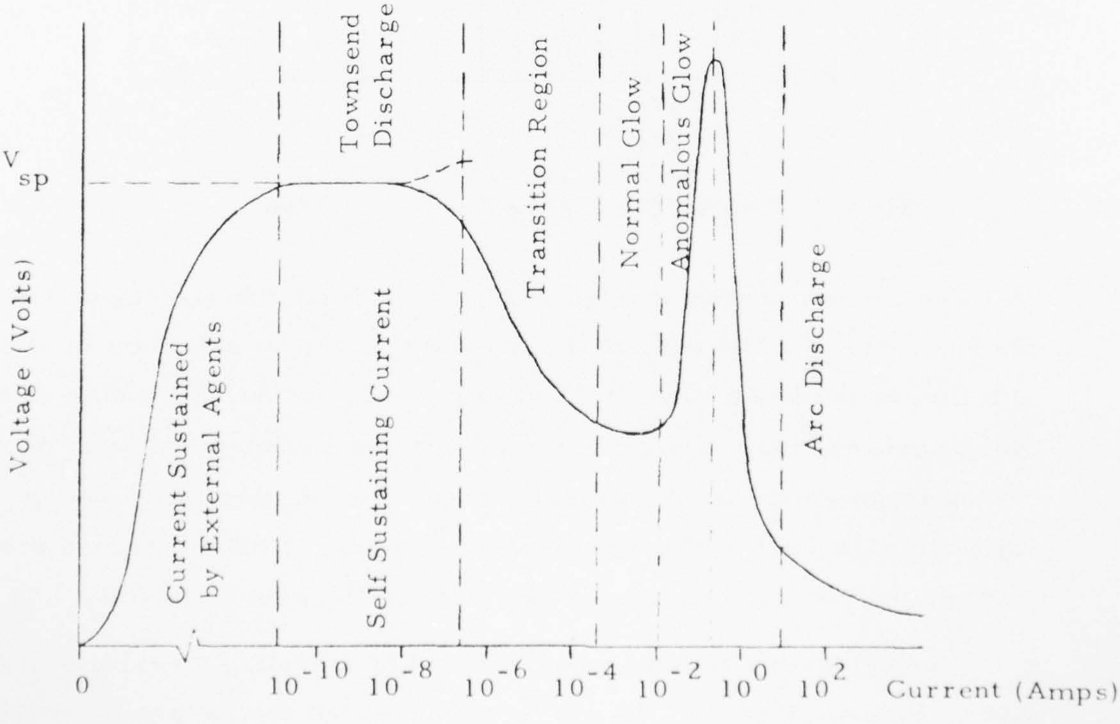


Figure 18. Schematic V-I characteristics of a gas discharge between flat parallel electrodes.

discharge regions. The arc discharge passing high currents at low voltage. An excellent description of the use of spark gaps is given in a report by Hart and Higgins(11) and their main conclusions will be briefly described here.

Typical volt-time curves of a GDT are shown in Figure 19 indicating an initial high clamping voltage. Its use in the protection of an

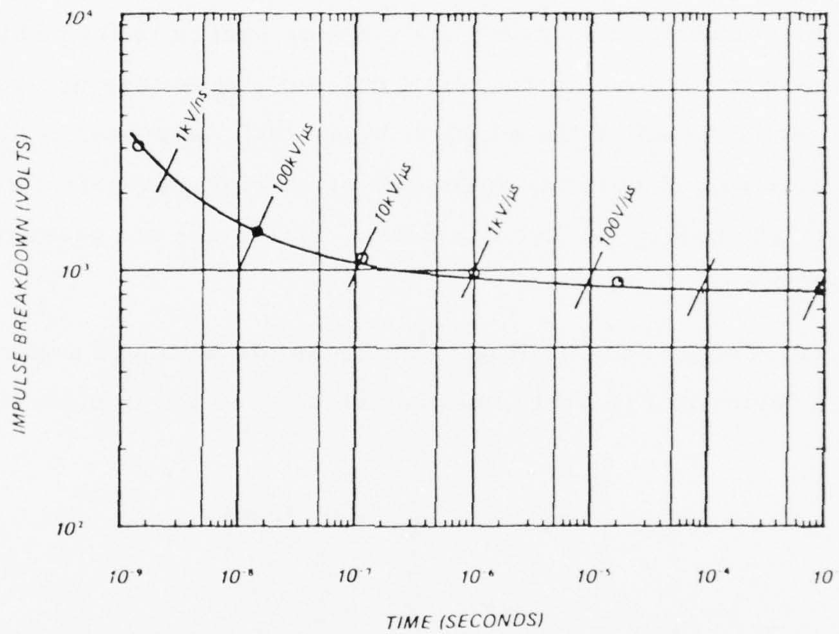


Fig. 19 Small MSP, P/N 2301-14 (Joslyn)

AC line surge is shown in Figure 20, but because the arc region can be sustained at a low voltage the AC voltage may be sufficient to allow a follow or holdover current. This holdover current, depending on the power source, may be significant and may be sufficient to cause damage to the electrodes. As the voltage passes through zero at the end of every half cycle the GDT will extinguish but at times, if the electrodes are hot and the gas ionized, it may re-ignite on the next half cycle.

The holdover current can be reduced by inserting a series resistor, but as Figure 21 shows, the current reduces but the voltage increases.

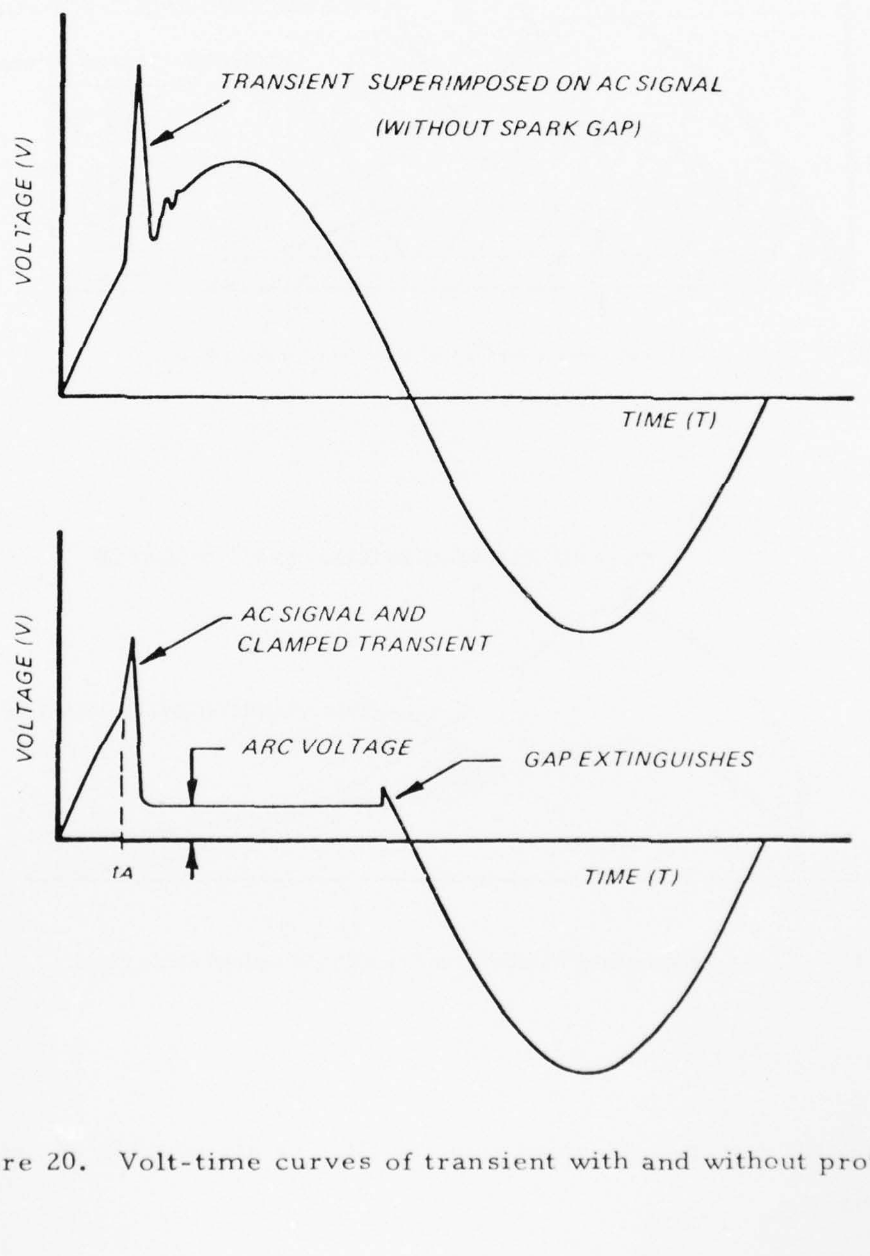


Figure 20. Volt-time curves of transient with and without protection.

The gas tube is an excellent device for protecting against high current surges but can not be used effectively in protecting low input impedance circuits. It is often an advantage to provide added protection to clamp

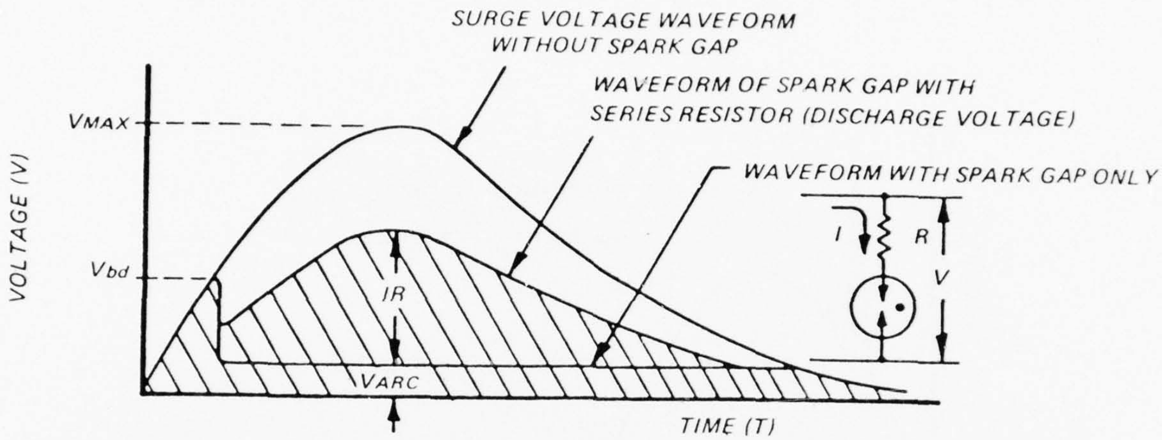


Figure 21a. Surge Voltage for Gap with Current Limiting Resistor

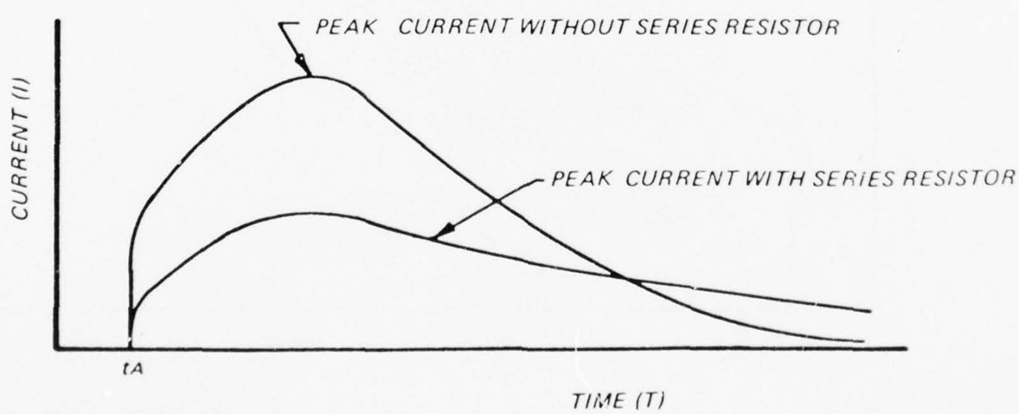


Figure 21b. Surge Current Waveform for Gap with and without Series Resistor

the initial voltage overshoot that the GDT is not capable of protecting against.

This can be done in several ways by designing hybrid circuits with the gas tube as the initial high current protector and a solid-state device to protect against the initial overshoot.

6.4 Hybrid Combinations

Several possible hybrid combinations utilizing the high surge current capability of spark gaps are shown in Figure 22. The advantages and disadvantages of each circuit have been discussed by Malone in reference 12, and the comments are shown with the circuits for convenience.

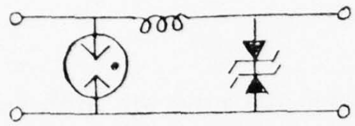
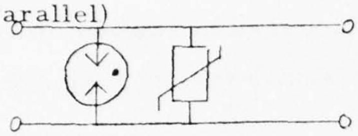
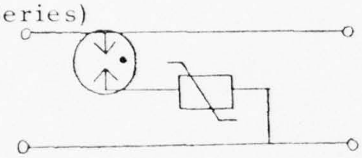
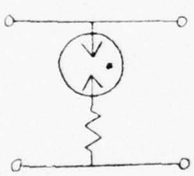
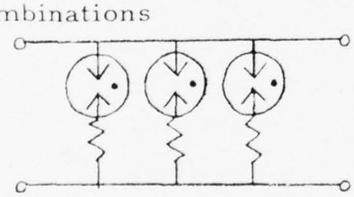
	ADVANTAGES	DISADVANTAGES
Spark Gap/Diodes 	Impulse spike of spark gap eliminated	Higher capacitance
Spark Gap/Variable Resistor (Parallel) 	Impulse spike of spark gap lowered	Increased resistive loading of line
Spark Gap/Variable Resistor (Series) 	Improved ability of spark gap to extinguish	1. Increased discharge voltage during surge 2. Varistor takes all surge
Spark Gap/Fixed Resistor 	Improved ability of spark gap to extinguish	Increased discharg voltage during surg
Parallel Spark Gap/Resistor Combinations 	1. Improved ability of spark gap to extinguish 2. Lower discharge voltage	1. Increased circuit complexity 2. Higher capacitance

Figure 22. Several possible hybrid combinations utilizing high surge current capability of spark gaps.

7.0 ACKNOWLEDGEMENTS

Much of the information presented herein has been taken from several reports which have been referenced, but the author wishes to make special mention of the material taken from data published by Dr. R.H. Golde.

8.0 REFERENCES

1. Llewellyn, S. K., Broadband magnetic waveforms radiated from lightning, M.S. Thesis, Florida Institute of Technology, Melbourne, Florida, 1977.

2. Anderson, J. G. and K.O. Tangen, Insulation for switching-surge voltages, in EHV Transmission Line Reference Book, Edison Electric Inst., New York, 1968.

3. Golde, R. H., Lightning protection, Edward Arnold Ltd, London, 1973.

4. Office of Naval Research, Code 450, Review of lightning protection technology for tall structures, Conference proceedings, 1975.

5. Bent, R. B. and S. K. Llewellyn, An investigation of the lightning elimination and strike reduction properties of dissipation arrays, Report No. FAA-RD-77-19, 1976.

6. Uman, M. A., Understanding lightning, Bek Technical Publications Inc., Carnegie, Penn., 1971.

7. Hill, R. D., Thunderbolts, Endeavour, 31, No. 112, 3-9, 1972.

8. Fisher, F. A., Instruction Bulletin 53E 9007, Fischer and Porter Co., Warminster, Penn., 1970.

9. Everett, W. W. Jr., Topics of intersystem electromagnetic compatibility, Holt, Rinehart and Winston, Inc., New York.

10. Druyvesteyn, M. J. and F. M. Penning, Electrical discharges in gases, Rev. Mod. Physics, 12, p. 87, 1940.

11. Hart, W. C., and D. F. Higgins, A guide to the use of spark gaps for electromagnetic pulse (EMP) protection, Report No. JES-198-1M-11/75, Joslyn Electronic Systems, Goleta, Ca., 1972.

12. Malone, E., Hybrid spark gap surge arrestors: A high frequency receive system arrestor for lightning and EMP protection, Report No. PEM-42, Joslyn Elect. Systems, Goleta, Ca., 1974.

THE LIGHTNING PROTECTION SYSTEM
AT TANEGASHIMA SPACE CENTER (TNSC)

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
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ABSTRACT

The main functions of Tanegashima Space Center (TNSC) are launching of rockets and satellites, satellite tracking and data acquisition and static firing test.

The Isokerdunic levels (IKL) in Tanegashima is statistically 30 to 33 days per year and the Osaki Launch Site will suffer from about 12 strikes per year, it is one of the most striked areas.

Protection of the equipments for these missions from lightning strikes is very important, so we have installed, though experimentally, lightning protection devices. Lightning protection for the electric power system is: 1) system is housed inside a concrete building which is protected by lightning rods, and 2) embedding and trough laying system using corrugated steel armoured cables. Lightning protection for the electronic devices and communication lines is 1) system is in concrete buildings which is protected by lightning rods of roof conductor type and 2) lines being embedded or laid in troughs using overvoltage protectors. Lightning protection for the building of storage and the handling facilities of explosives and dangerous objects is a system which uses independent lightning rods and overhead grounding wires.

1. Introduction

The main function of the Tanegashima Space Center (TNSC) include launching of rockets and satellites, satellite tracking, data acquisition and static firing test.

We are paying considerable attention to lightning protection system in order to protect the equipments for the fulfillment of these functions. In the following we introduce our considerations about the plan of lightning protection and their several example at the Osaki Launch Site, and explain briefly the lightning alarm devices which have been tentatively installed.

The Osaki Launch Site is the main site in TNSC and the largest in Japan (for launching rockets and satellites) and it is expected to play an important role for the future launching of applications satellites.

2. Design Consideration

2.1. Thunderstorm days per year at the Tanegashima Island

Fig. 1 shows Isokeraunic levels (IKL) in Japan, which are the average in about 20 miles-by-20 miles areas. From this figure, we find that in Tanegashima district the IKL level is 30 to 33 days per year, indicating it is one of the largest IKL, level areas. If, in Japan assuming that IKL level is 33 days per year, we estimate the number of lightning strikes to the earth per year at TNSC, which is located 30 N, according to FAA report,[1] it is 1.5 strikes/year/km^2. It is inferred, therefore, that the Osaki Launch Site of about 7.5 km^2 will suffer from about 12 strikes/year.

2.2. Regulations for the lightning protection in Japan

As there are the Lightning Protection Code and the Electrical Code in the rules of NFPA (National Fire Protection Association) in the United States, there are regulations of similar contents in Japan, which provide minimum requirements about lightning protection. As to the structures of lightning protection devices and the method of grounding, there is a standardization presented by the Japan Industrial Standard (JIS) and the Japan Electrical Construction Association (JECA) suggests some kinds of facilities according to the differences of buildings in the actual application, as seen in Table 1.[2]

2.3. Design principle of lightning protection at TNSC

Using the data of IKL and those in Table 1, we employ the design principles of lightning protection system for the Osaki Launch Site, following not only the minimum requirements, but the special design principles described below. These principles can be applied to the buildings of the other stations.

2.3.1. Lightning Protection for electric power systems

a. Power plants and substations are of indoor type, being housed inside a building of reinforced concrete, and the building itself is protected by lightning rods. The outer view of the power plant is shown in Fig. 2 as an example.

b. We employ the embedding and trough laying systems for the feeders of high and low voltage, using corrugated steel armoured cables instead of overhead wiring system.
The corrugated steel armoured cable is effective to lower the earth potential when it is grounded. In addition lightning arresters are attached to the sending and receiving end of high voltage cables.

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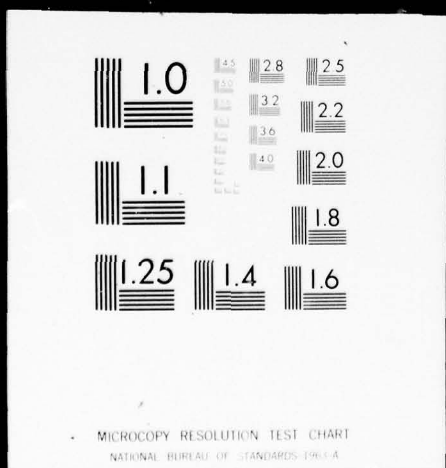
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MICROCOPY RESOLUTION TEST CHART
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2.3.2. Lightning Protection for the electronic device and communication line

a. The electronic devices are as a principle accommodated in a building of reinforced concrete which is protected by lightning rods of roof conductor type.

b. Outdoor antennas are protected by independent lightning rods, which are installed by taking, the situations of the places into account. An example is shown in Fig.3.

c. The communication cables are either embedded or laid in troughs and leading-in points of the cables are protected from the lightning surge using overvoltage protection devices. But we don't use buried bare cables of common rod counterpoise system or interconnecting of the separate electrode system, although it was recommended by FAA.[3]

2.3.3. Lightning Protection for the building of storage and the handling facilities of explosives and dangerous objects

a. According to Table 1, we applied augment protection to those buildings, where, in principle, independent lightning rods and overhead grounding wires are used, so that the protection angle may become below 45 degrees. An example of Rocket motor storage is shown in Fig.4.

b. Grounding rods are attached to every independent lightning rod, which is interconnected by use of buried bare cables. When necessary, the total grounding resistance is made lower, using auxiliary electrodes.

3. Actual examples

3.1. Mobile Service Tower (MST) for N-launch viecle

As shown in Fig.5 , MST is about 55 meters high, being composed of truss structure and regarded as a kind of cage. The four lightning rods mounted on the top of MST are connected to the grounding rods respectively through down conductors along the corners of MST. Since MST is moved along the rail by about 80 meters, these grounding rods are equipped at both the viecle assemble position and the retrograde position, being 8 sites in all and separated into two groups. These grounding rods are interconnected by buried bare cables to rails, launch pads and the grounding rods of umbilical tower, as well as to the surrounding grounding rods of liquid oxygen storage, fuel storage and nitrogen gas storage. Thus, the elevation of earth potential is minimized as well as counterpoised over the area about 150 meters long and 100 meters wide, including the site of the launch deck, so that the viecle, the auxiliary ground support equipments, the dangerous products and the explosives are protected. In addition, according to the safety manual, the works are interrupted and workers are evacuated in the viecle launching area including the inside of MST, when thunder cloud approaches.

3.2. Dangerous Areas

Facilities for the rocket motor storage and handling are called "Dangerous Area", which include rocket motor storage, ignitor storage, rocket motor checkout building and spin test building. These facilities are protected through augment protection as described in section 2.3.3, using independent lightning rods, overhead ground wires and buried bare cables. Fig.6 shows an example of the spin test building. These protection system is so designed that the buildings covered with in 45° angle relative to a vertical plane including the lightning rods and overhead grounding wires can be protected.

Each facilities in the dangerous area is placed in the bottom areas between gentle hills, in order to minimize the effect to the surrounding facilities in case of explosion or other accidents, so that the soil humidity is very high, resulting in specific resistance of the soil of as low as 20 to 30 ohms-m. Hence, grounding resistance becomes 4 to 8 ohms with respect to each grounding rod, and the total grounding resistance obtained by connecting through buried bare wires is 0.2 to 0.4 ohms, so that minimization of the earth potential elevation in case of lightning strike can be well expected.

4. Lightning alarm device

4.1. Status of lightning alarm system in Japan

The objects of the recent development of the lightning alarm system in Japan can be divided into three cases: The first is the development of the system to protect power transmission lines from lightning strikes. The second is the thundercloud warning system of Defence Agency of Japan which has been reported to have been installed recently at the Komatsu Base of the Air Self Defence Force,

for the purpose of warning the air area around the air base. The third is the development of simple apparatus for leisure industry, for example, which protect Golf players at Golf countries.

(1) The systems for the protection of electric power feeders include the thundercloud warning system installed by the Tokyo Electric Power Company which forecast the occurrence of thundercloud 20 minutes beforehand with 50 percent probability by use of weather radars and data processing apparatus. The Shikoku Electric Company utilizes information from discharge waves obtained from many observation stations to cut off or transfer the power supply system.

(2) Although details are not known, it is reported that the system of The Defence Agency of Japan uses a thundercloud sensing radar and two sets of direction finders and 8 sets of electric field meters to monitor the range within 50 km in radius.

(3) As simple devices for public use, there are the systems which count the thundercloud discharges and give a warning of thunderstorm when the discharge density exceeds a certain level in a certain interval, or give a warning when the charge of electric field is senced. Both systems, however, can not detect the range and the direction of the thundercloud.

4.2. Test of lightning strike warning devices at TNSC

Two kinds of lightning strike warning devices that have been designed for public use have recently been installed at TNSC for the purpose of test. By use of these devices we have examined the characteristics of thunderstorms at Tanegashima Island and attempted to select a practical thundercloud sensor for further development of thundercloud alarm system. One of the devices tested is of lightning discharge counting type consisting of a

25 KHz band receiver, a pulse counter, a display unit and a recorder. The receiving antenna is of the type shown in Fig. 7 . The pulse counter is reset every 5 minutes automatically, and when 3 successive signals are received, a noticesignal is displayed, and 7 successive signals are received, a warning signals displayed. By this device, it is reported that the approach of thundercloud can be noticed in the range of 20 to 30 km and, in the range of 10 km, it can give a warning. The TNSC has not yet examined the relationship between the discharge counts and the range with this device. This device is unable to distinguish between the intracloud discharge, the stepped leader and return stroke. The attached antenna is omni directional, so that it can not discriminate the direction with only a single device. The other device tested is of electric field measuring type. This device gives a warning on the basis of the density of thundercloud discharge, using a rotary type electric field measuring instrument, as shown in Fig. 8, which measures the electric field associated with the occurrence of thundercloud and detects thundercloud discharge that synchronizes with lightning, so that the thundercloud discharge is distinguished from the discharges of the other causes. Fig. 9 shows a schematic of this device, and Fig. 10 shows an example of the variation of electric field in the case of strike to the earth recorded in TNSC. This device, like the former device, can neither determine the range and direction of the thundercloud nor measure the absolute electric field intensity.

5. Conclusion

In this report the lightning protection system of TNSC has been outlined. Our experience can not be said sufficient at present, and we consider to make further study and development so that we can establish a more economical and effective system. We hope that the thunderstorm warning or protection system capable of predicting the thunderstorm reliably at least one hour beforehand can be established, so that we can protect those persons who are encaged in dangerous works or outdoor works and treat properly dangerous products.

We would like to comment that the FAA reports were very useful to our consideration of the present lightning protection system at TNSC.

Reference

(1) FAA-RD-75-215-I : GROUNDING, BONDING, AND SHIELDING PRACTICES AND PROCEDURES FOR ELECTRONIC EQUIPMENTS AND FACILITIES

(2) JECA 1010 (1973): REPORT ON THE PROTECTION DEVICE FOR FACILITIES

(3) FAA-RD-75-215-II: GROUNDING, BONDING, AND SHIELDING PRACTICES AND PROCEDURES FOR ELECTRONIC EQUIPMENTS AND FACILITIES

(4) Mitsubishi Electric Corp. Technical Report, Vol.45, No.2, 1971: Thundercloud Warning System and Communication System

Table 1. Application of Lightning Protection System

KIND OF FACILITIES	CONSTRUCTION OF BUILDINGS		AREA					
			LESS THAN IKL 30			TO EXCEED IKL 30		
	BUILT OF	HIGHT (M)	DOWN TOWN	SOLITARY HOUSE	TOP OF HILLS etc.	DOWN TOWN	SOLITARY HOUSE	TOP OF HILLS etc.
GENERAL	WOOD	< 20	N.N.	S	R	N.N.	S	P
	R.C.	≤ 20	N.N.	N.N.	R	N.N.	R	A
		> 20	R	R	A	R	A	A
SCHOOL,	WOOD	< 20	R	R	R	R	A	P
THEATER,	R.C.	≤ 20	N.N.	N.N.	R	R	R	A
etc.		> 20	R	R	A	A	R	A
FACTORY,	WOOD	< 20	R	R	R	R	A	P
WAREHOUSE,	R.C.	≤ 20	N.N.	N.N.	R	R	R	A
etc.		> 20	R	R	A	A	R	A
MAGAZINE,	WOOD	< 20	A	A	A	A	A	P
FUEL STO-	R.C.	≤ 20	R	R	A	A	A	A
RAGE, etc.		> 20	R	R	A	A	A	A

R.C. : REINFORCED CONCRETE

N.N. : NOT NECESSARY PROTECT

S : SIMPLE PROTECTION (Apply the simple protection method according to JIS)

R : REGULAR PROTECTION (Apply the regular method according to JIS)

P : PERFECT PROTECTION (Protect by the cage)

A : AUGMENT PROTECTION (Augment than the regular protection)

Fig.1. Isokerdunic level (IKL) in 20 miles section for Japan

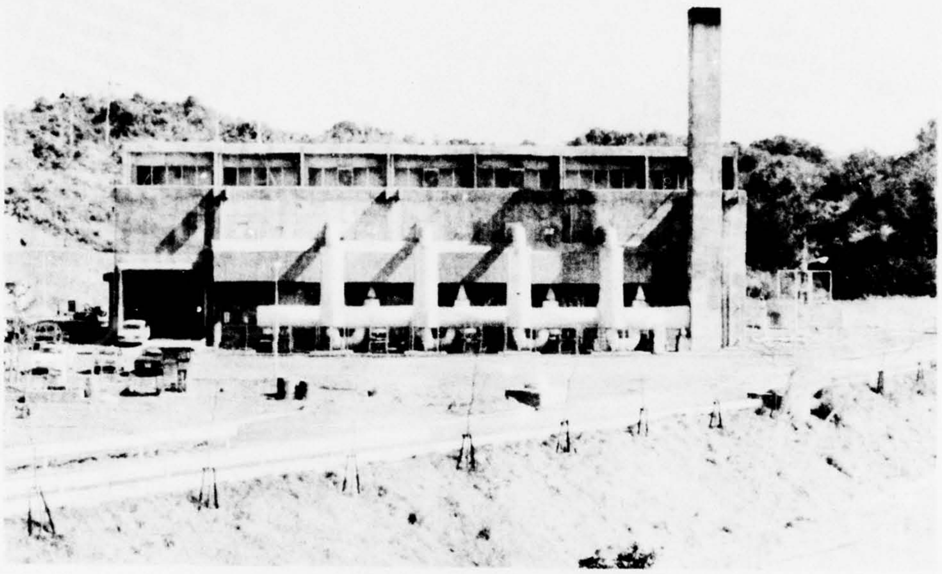

Fig. 2. Osaki power plant protected by the lightning rods

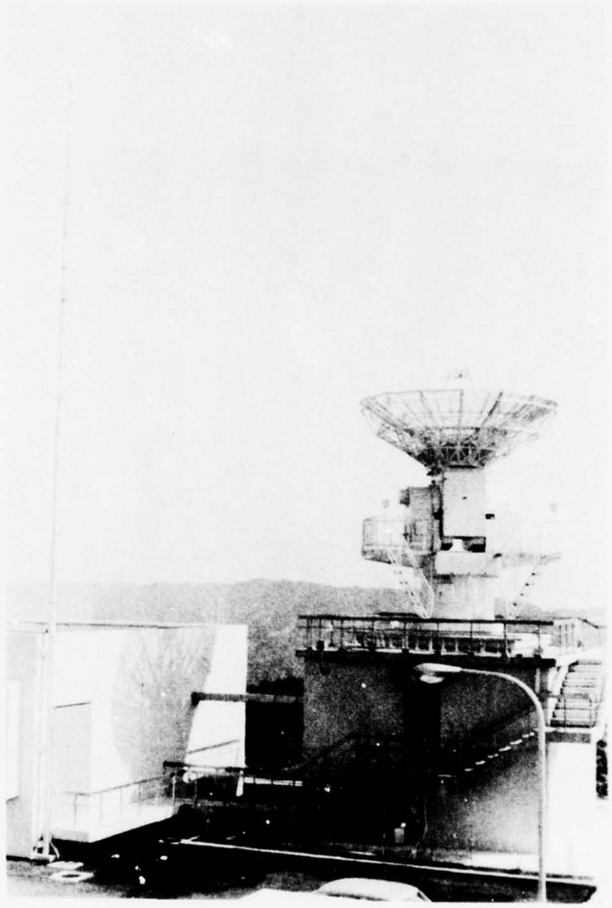

Fig. 3. Rader antenna, protected by the independent lightning rods

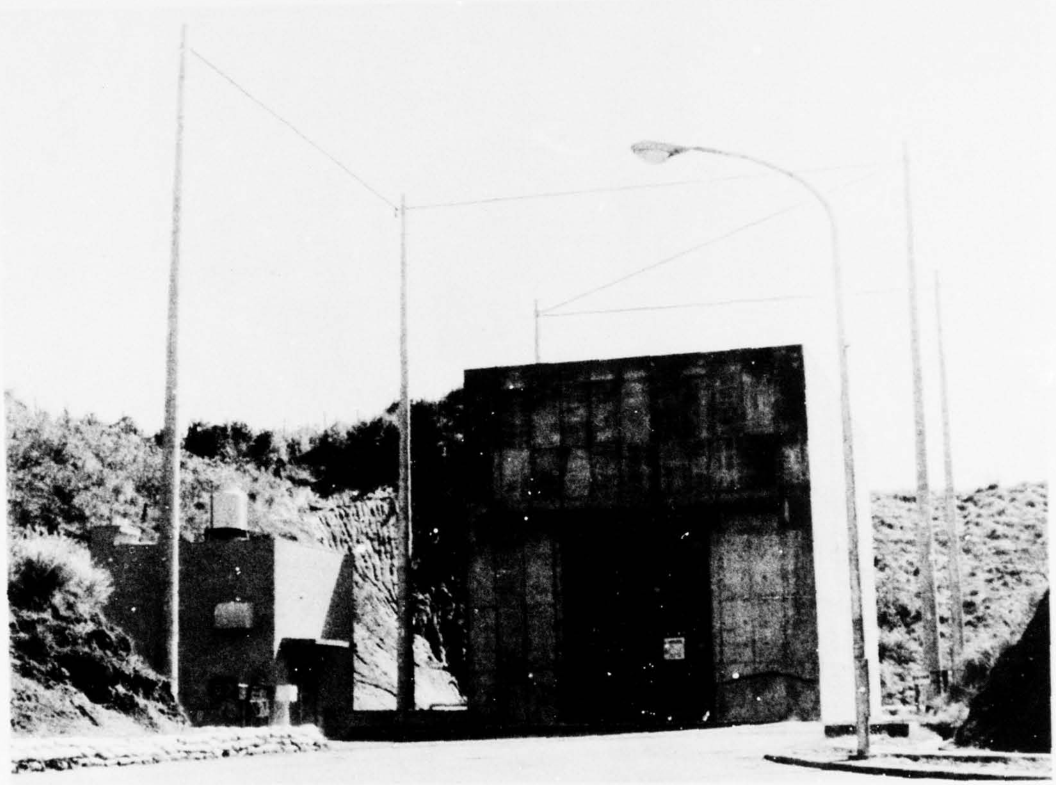

Fig. 4. Independent lightning rods and overhead ground wire for slid motor storage

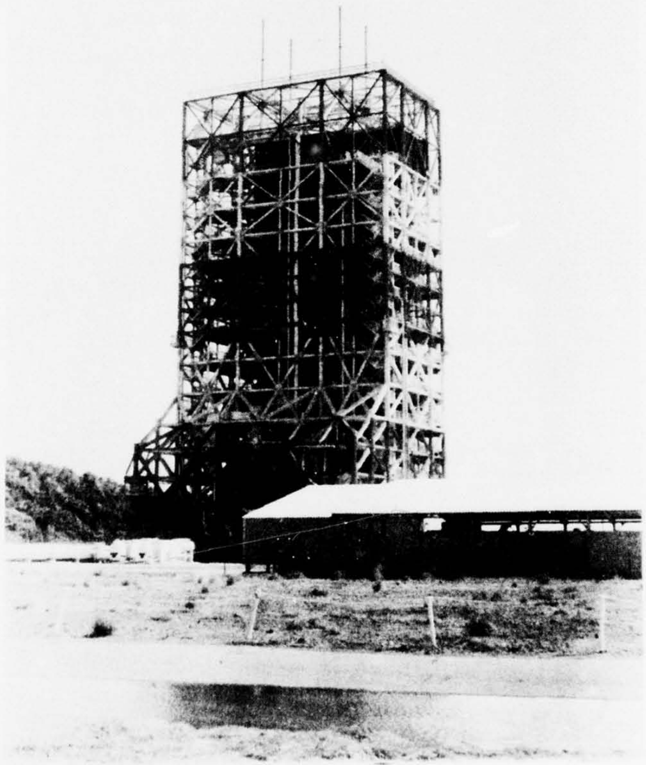

Fig. 5. Mobile service tower for
N-launch viecle

Fig. 6. Augment protection with independent lightning rods and overhead ground wire for spin test building

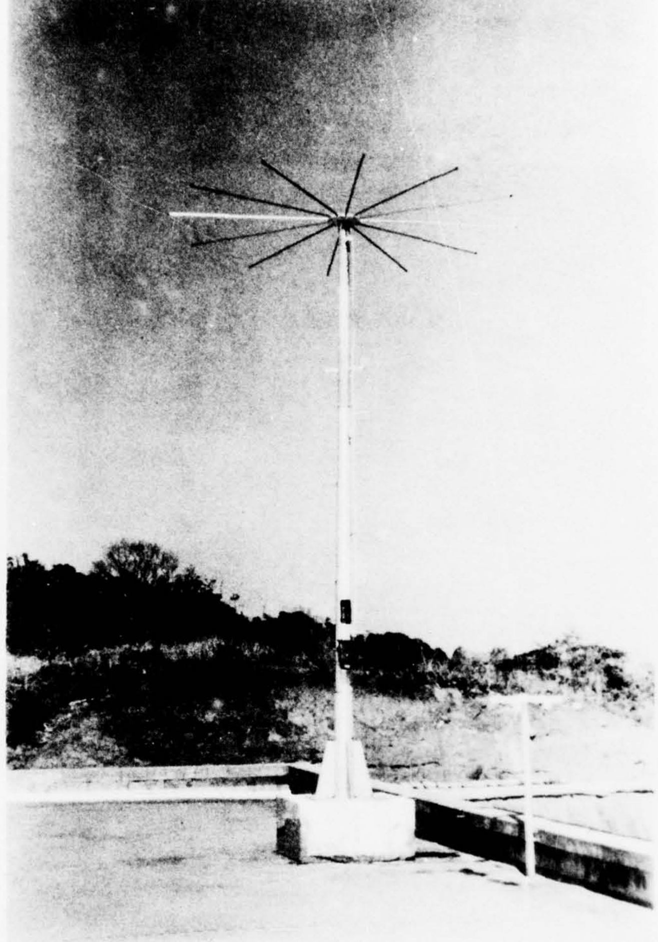

Fig. 7. Antenna of the discharge signals counting type lightning alarm device

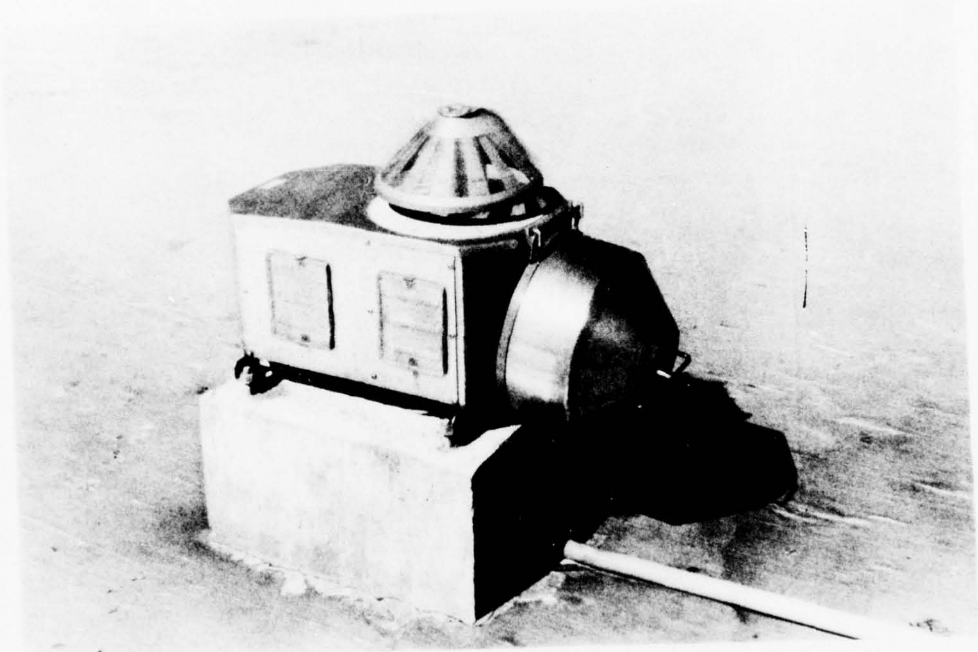

Fig. 8. Rotary type electric field measuring instrument

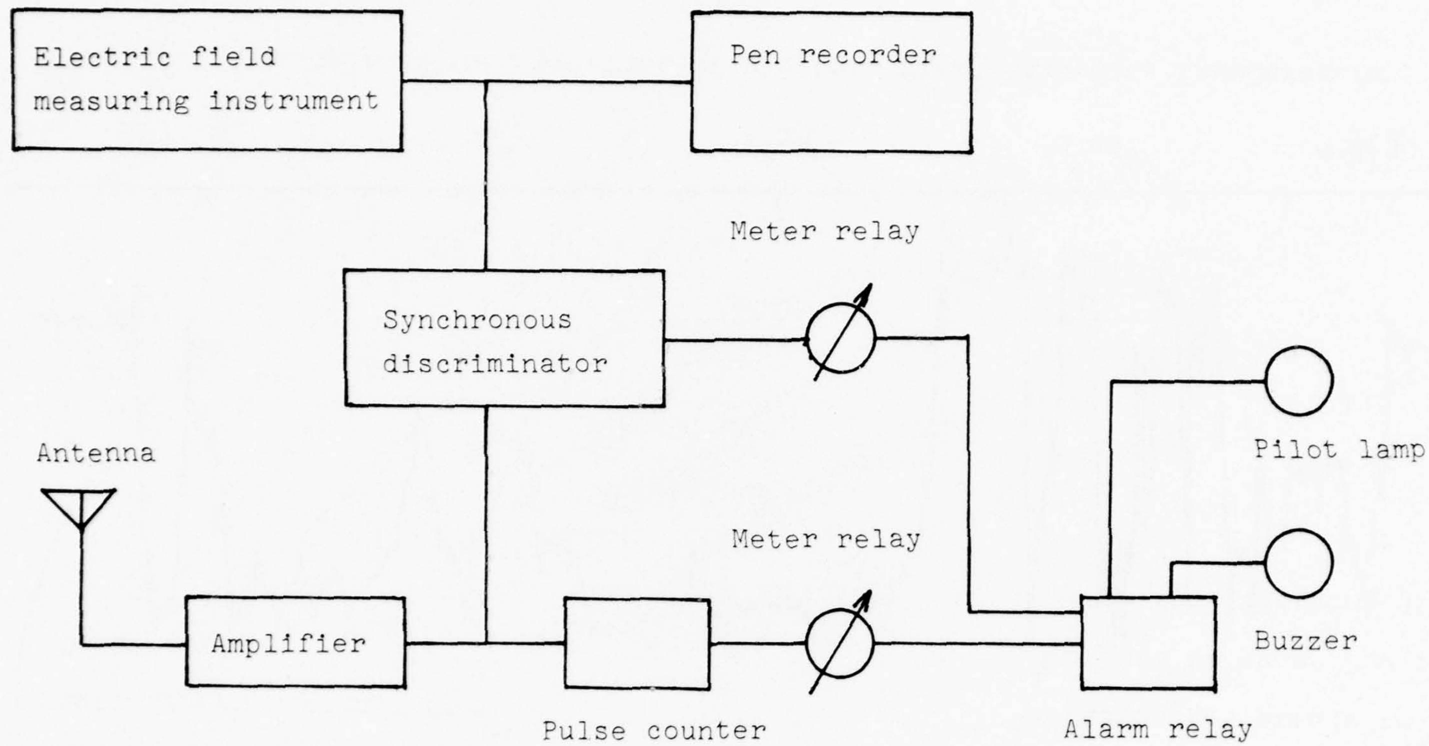

Fig. 9. Schematic of the electric field measuring type lightning alarm device

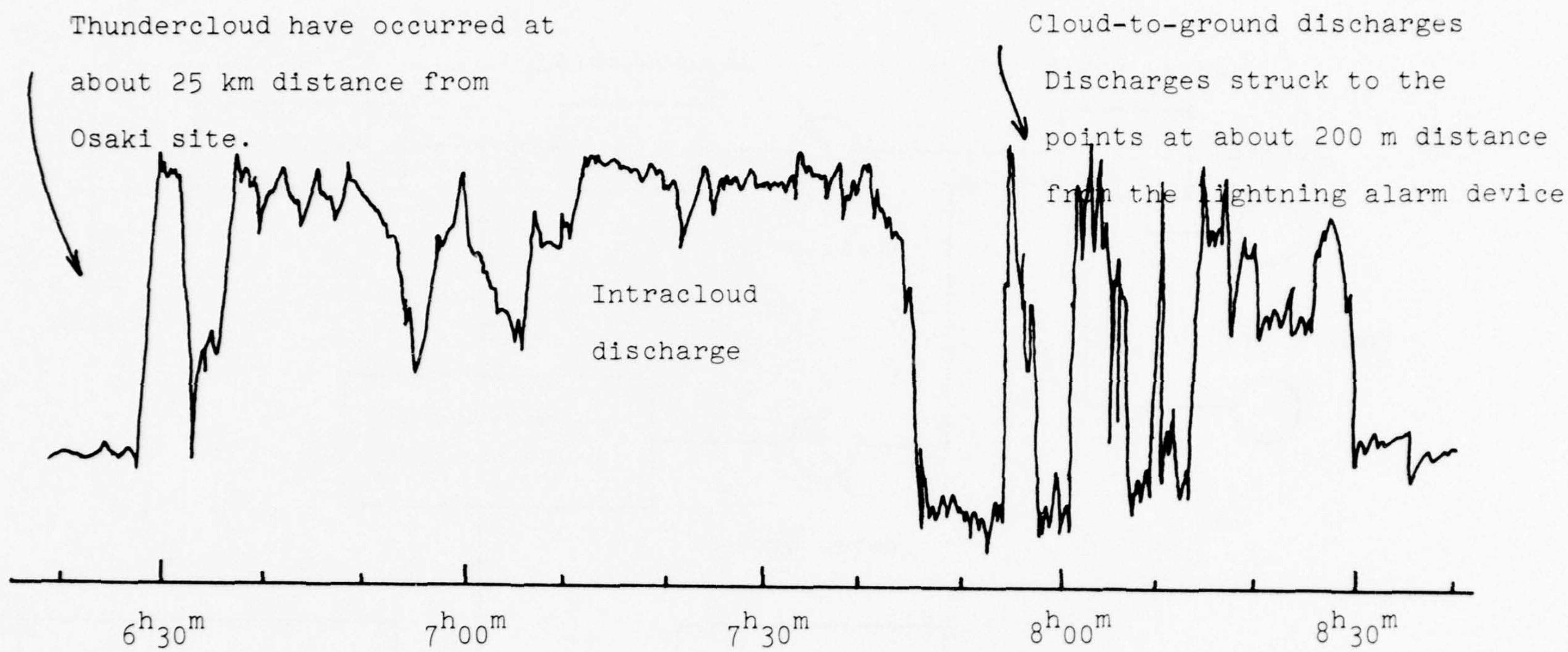

Fig. 10. A sample of the variation of electric field caused by thunderstorm

PROTECTION FROM LIGHTNING - INDUCED EFFECTS

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

A lightning rod or air terminal along with a good conducting path to ground provides a safe path for the lightning current to reach ground without causing damage to wood or other non-conducting structures. Modern steel structures are not normally susceptible to such lightning direct effects. However, the voltages and currents induced by lightning currents that flow in a conducting structure can cause damage or upset in sensitive electronic or other electrical equipment. They can also cause dangerous sparking in areas where explosive gases, vapors, dusts and other ignitable materials are present. Sparking can also initiate a short circuit current which is then sustained by the circuit voltage causing failure of computer or control circuitry. Personnel may be exposed to moderate electric shock.

The induced effects result from the interaction between susceptible conductors and the electromagnetic fields associated with the lightning. The magnetic field changes inside a structure, that produce induced voltages, depend on the lightning current flow paths in the structure. These induced effects can be minimized by lightning current control techniques. The current distribution can often be changed so as to minimize the magnetic field in the region of the equipment to be protected. This concept is applicable to many shielding and ground current flow problems.

PROTECTION FROM LIGHTNING - INDUCED EFFECTS

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1.0 INTRODUCTION

Ben Franklin found that by using lightning rods, connected to an earth ground, a safe path could be provided to ground for the lightning currents without damage to wood frame or other nonconducting structures. Modern steel structures are not normally susceptible to lightning direct effects which are usually burning and welding at the points of arc contact. However, currents and voltages may be indirectly induced in the conductors of sensitive electronic or electrical equipment which is located in the structure. This equipment may be damaged or upset by the currents and voltages induced by nearby lightning currents in the structure. Dangerous sparking, in areas where explosive gases, vapors, dusts and other ignitable materials are present, may occur. Sparking can initiate a short circuit current which is then sustained by the circuit voltage, causing failure of computer or control circuitry. Personnel may be exposed to moderate electric shock.

Induced voltages and currents may be reduced by shielding the equipment circuits and cables, using protective devices and by controlling the current paths about the structure so as to reduce induction in the region where the susceptible equipment is located.

2.0 INDIRECT EFFECTS

Currents and voltages resulting from a lightning strike in conductors that are not directly contacted by the lightning channel or in the main lightning current paths are considered indirectly produced. These include induced voltages and currents inside enclosures or resulting from a common connection such as a ground. In contrast, the direct strike contact effects include burning, eroding, blasting, deformation, and other structural damage. High pressure shock waves and large magnetic forces are associated with lightning strokes having high peak currents.

When a thunderstorm charged region is overhead, the charge may start a random stepping motion toward the ground in the form of a leader with a velocity of about 100 kilometers per second or 1/3000 the speed of light. The trip from cloud base to ground takes about 20 milliseconds. The high electric field produced when the leader approaches the earth causes displacement and point-discharges to flow from objects on the earth such as buildings, trees, and people. When the leader tip is close to the ground (about 70 meters), streamer discharges from the earth propagate upwards to meet it. Streamer currents range from 10 to 1000 amperes. People conducting these streamers may feel the equivalent of a hammer blow on the head. They are usually knocked down, stunned, and

may be temporarily paralyzed. They usually can be saved by prompt application of first aid techniques. A few of the streamers may reach the leader and become part of the main lightning channel. The rest terminate when the electric field collapses as the electric field is suddenly reduced when the channel is completed. People sharing current with the main channel are usually burned severely at the points of lightning entry and exit and heavily shocked. Some of these people may survive if the shared current is relatively small or of short duration.

Figure 1 illustrates how a person may share in a lightning stroke by standing close to an outdoor isolated pole or tree. A side flashover may occur to a person near the pole. Part of the ground current may flow between the legs of a person walking nearby. Figure 2 shows that a worker carrying a pipe in an open area is susceptible to the induced streamer hazard and may also share some of the stroke current.

2.1 Electric Field Induction

A thundercloud induces a charge on the Earth opposite to that of its base. When a lightning discharge occurs, changes in electric field may be as great as 15 kilovolts per meter as far as 3 miles away. The changes in electric field induce high voltages on objects, particularly on long insulated wires such as power lines and ungrounded fences. The redistribution of these charges manifests itself as a current flow through the impedances of any grounding conductors and appears as a voltage across these impedances. Lightning leaders that lower a charge from the cloud to ground can cause very high prestrike voltages in transmission lines, even if they do not contact the line directly. While direct strokes cause more damage, induced voltages are more numerous and can cause outages on low voltage lines or can damage connected equipment. Induced voltages of one million volts have been frequently recorded on overhead transmission lines.

Telluric or earth currents can flow in buried cables during thunderstorms, and large transient voltages may be coupled into these cables. Impedances between the ground points of an earthed multiple ground system also share earth currents. If the system can be isolated, a single ground point may be used. Where ground currents flow, the cabling between grounded systems must be carefully shielded.

2.2 Magnetic Field Induction

Electromagnetic coupling exists where a voltage is induced in a circuit magnetically coupled to the current carrying conductors. For instance, in Figure 3, voltage E is magnetically induced in loop A by the field produced by the changing current in conductor B. Conductor B could, of course, be any conductor that is carrying the lightning current, including the lightning channel. The voltage induced in a single-turn isolated loop is the line integral around the closed path of the electrical field intensity E in volts per meter, $\oint \overline{E} \cdot \overline{dl}$. This can be related to the rate of change of the magnetic field by using Stokes's

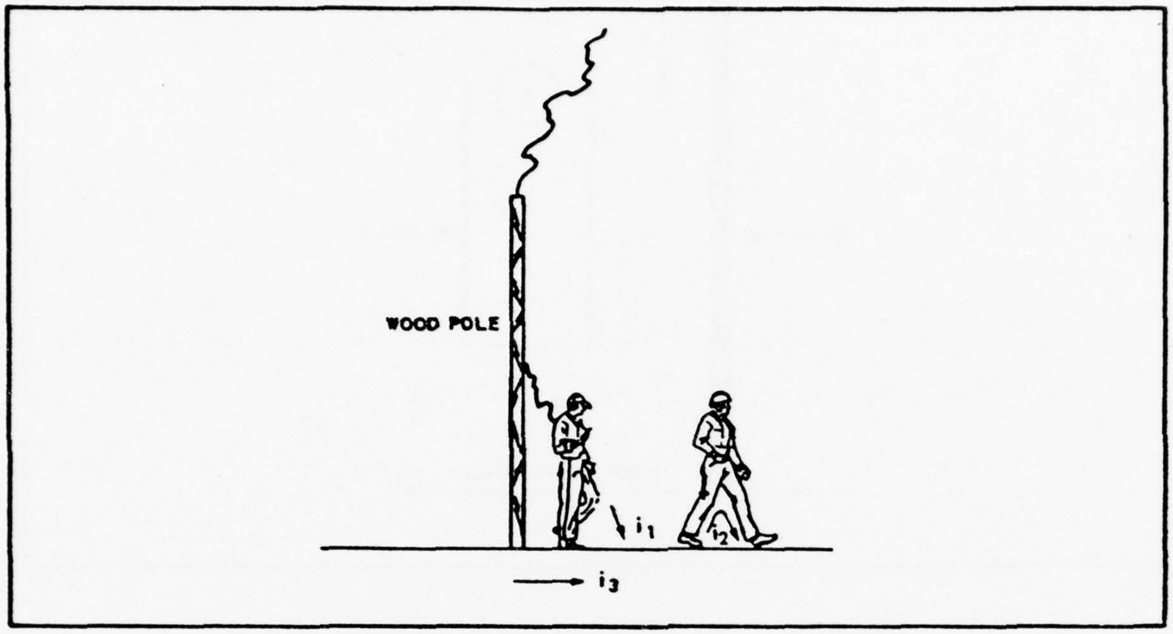

Figure 1. Indirect Side Flash and Shared Ground Step Current Hazards

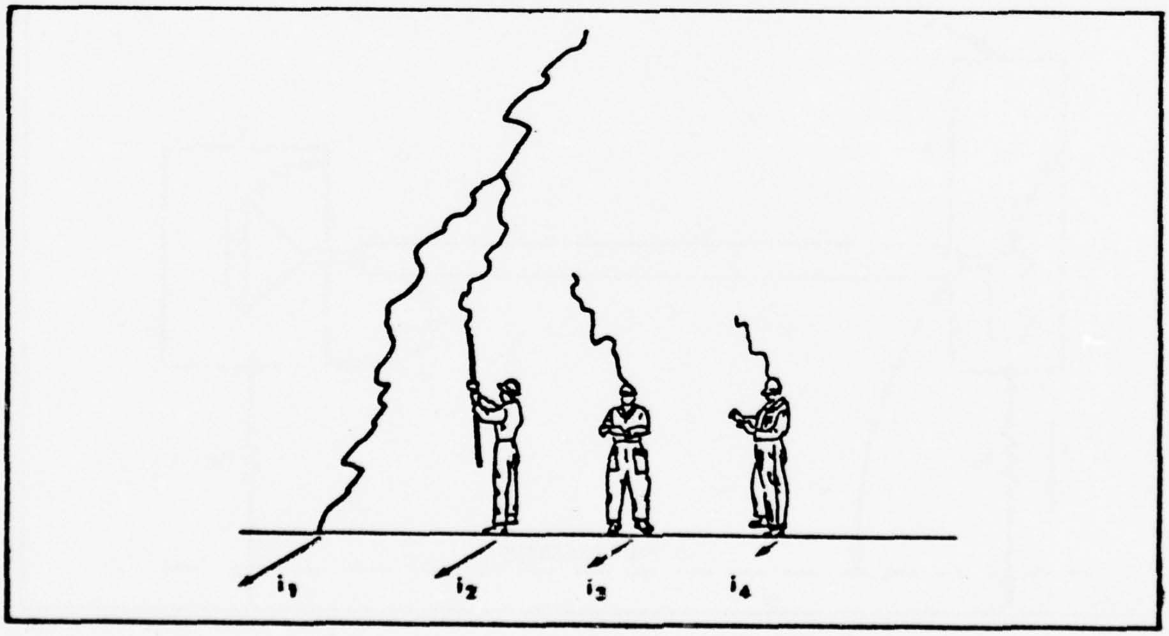

Figure 2. Shared Current and Induced Streamer Hazards

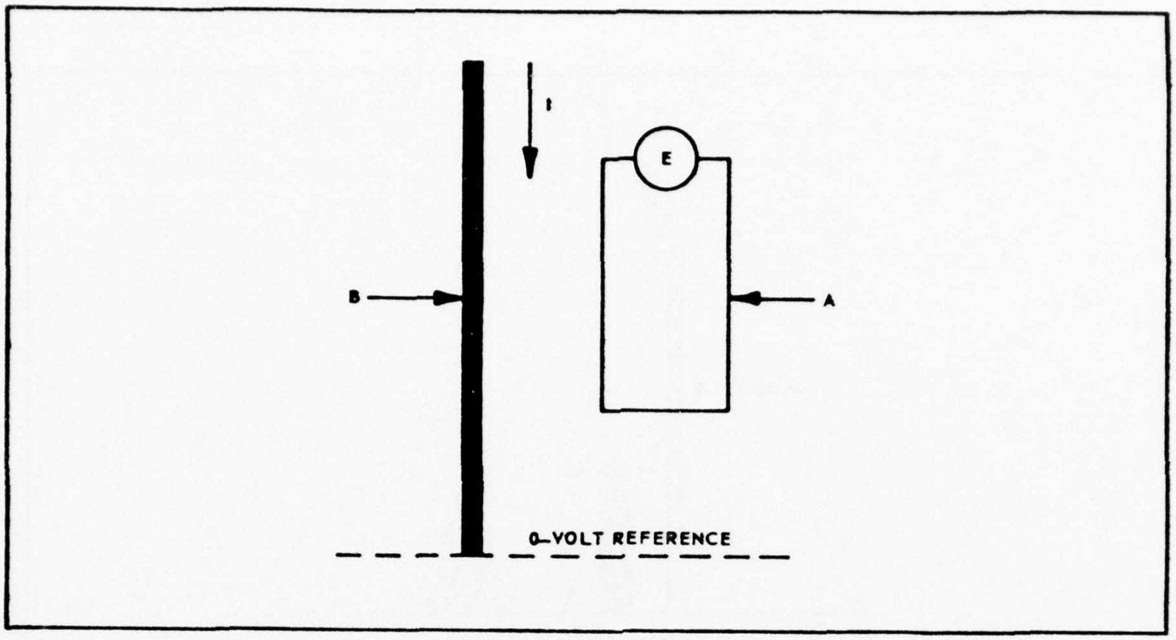

Figure 3. Magnetically Induced Voltage

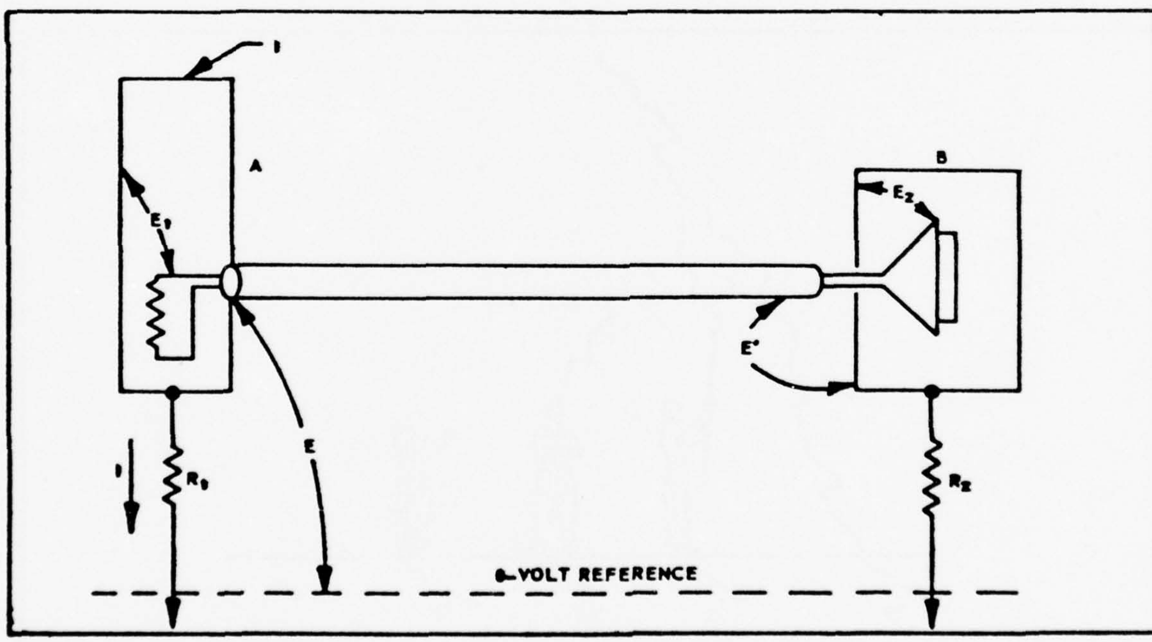

Figure 4. Resistively Coupled Voltage Due to Lightning

theorem, $\oint \overline{E} \cdot \overline{dl} = \int \nabla \times \overline{E} \cdot \overline{ds}$, and one of Maxwell's equations, $\nabla \times \overline{E} = -\partial B/\partial t$, known as Faraday's law. The induced voltage reduces to the familiar form:

$$\text{Volts} = -(1/\partial t)\partial \int \overline{B} \cdot \overline{ds} = -\text{Area}\,(\partial B/\partial t) = -\partial \phi/\partial t \qquad (1)$$

Therefore, the voltage induced in the loop is equal to the rate of change of the normal component of the flux linking it. One volt is induced in a single turn of a one square meter loop by a magnetic field rate of change of one tesla per second.

2.3 Resistive Coupling

A lightning stroke current I, Figure 4, may terminate in the enclosure A and then flow into earth through the ground resistance R_1, producing a voltage E between the enclosure and ground. If a cable shield is connected to the enclosure as shown in Figure 4, this voltage appears on the cable shield relative to earth ground, but not relative to the enclosure A. The cable runs to another enclosure B, grounded through R_2. If a single point ground is used only on the cable shield at enclosure A, the voltage E'exists between the cable shield and enclosure B. Since no current flows in R_2, the ground resistance of enclosure B, all the voltage E appears across the discontinuity. The voltage E_2 between the circuit and enclosure B will be some fraction of E', depending on the circuit impedances. For a 100 kiloampere stroke and a one ohm ground, E'could be 100 kilovolts. Of course, arcover would occur before this voltage is reached. The most direct way of minimizing E' and E_2 is to connect the cable shield to enclosure B and allow the shield to conduct a portion of the stroke current. This illustrates the need for an overall shield, grounded at both ends, for lightning protection of cables between two enclosures. Good earth grounding of both enclosures does not obviate this requirement.

3.0 ELECTRIC AND MAGNETIC SHIELDING

The shielding effectiveness of an enclosure against electric fields first decreases at a rate inversely proportional to frequency and then increases with frequency as the depth of penetration becomes much less than the thickness of the material. As an example of electric field shielding, the minimum shielding effectiveness of a 1/16-inch wall aluminum sphere, 36 inches in diameter, would be about 220 decibels at 50 kilohertz.

Magnetic shielding for an enclosure is difficult to attain at low frequencies. A high permeability material may be used to duct the field around the enclosure. This method is generally not practical for ordinary shielding because of cost and weight. At intermediate frequencies, shielding effectiveness increases in proportion to the frequency due to the reflections from the conducting enclosure surface as a result of currents induced on the surface. Shielding effectiveness is reduced if these currents are prevented by cracks or apertures in the surface. At high frequecies, shielding by absorption or skin effect again predominates. A 36 inch aluminum sphere, used as an example for electric field shielding, has a magnetic shielding effectiveness of about 80 decibels at 50 kilohertz. A steel conduit or enclosure provides better shielding over the lightning spectrum than copper or aluminum. The same attenuation is obtained at about 1/10 the frequency so that a longer pulse would be effectively attenuated. Large atten-

uations are obtained for relatively thin sheets of the order of 0.05 inch thick. Magnetic coupling through apertures may exceed diffusion coupling, especially at high frequencies.

With good shielding the voltage inside the shield can be reduced to the order of the shield-resistance voltage drop. Shield braid generally does not offer adequate shielding at high frequencies, but is adequate over most of the lightning frequency spectrum. Conduit and cable trays can be made to provide good shielding. Cables can also be double shielded to improve shielding effectiveness, and circuits can be isolated on signal pairs to separate the circuit from the shield resistive voltage drop.

4.0 CURRENT CONTROL FOR MINIMIZING INDUCED EFFECTS

Tall structures may attact severe lightning strokes from distances 10 times the height of the structure. For a 500 foot tower the radius of attraction is one mile. The induced voltages inside a structure, due to a direct stroke to the structure, can be reduced by controlling the current flow so as to minimize the magnetic flux produced inside the structure. This can be accomplished by causing the current to flow symmetrically about the structure so as to cancel the magnetic flux in the structure in the region where susceptible equipment or cabling is located. As an illustration, for 16 vertical conductors arranged as shown in Figure 5, there is a zone of negligible induction in the center for equal currents in all conductors. At the boundary of this zone the magnetic field is reduced by a factor of 2000 (66 decibels) as compared to the field between two of the wires. The reduction is greater inside the zone. Inside a structure, equipment susceptible to lightning transients should be located in the zones of negligible induction.

Figure 6 illustrates a technique for obtaining symmetrical current flow about a structure using an insulating mast, shield wires and ground conductors terminated in equal ground impedances. The shield wires may be connected to building steel if symmetrical current flow can be provided by the structure. If not, insulated cables might be used. The insulation need only be adequate for the difference between the cable voltage and that induced in the building steel.

5.0 VERIFICATION TESTING

The ability of equipment to withstand the indirect effects of lightning must be verified by analysis or test. A diagram of the various transient levels is shown in Figure 7. A protector may be used to reduce the transient to a specified level below the transient control level (Z margin) relating to the degree that the actual transient level is known. Depending on the criticality (X margin) of the circuit, a transient design level is specified above the control level and, depending on the extent to which the actual equipment susceptibility is known (Y margin), a susceptibility (upset) level is set. The vulnerability (damage) level is above the susceptibility level.

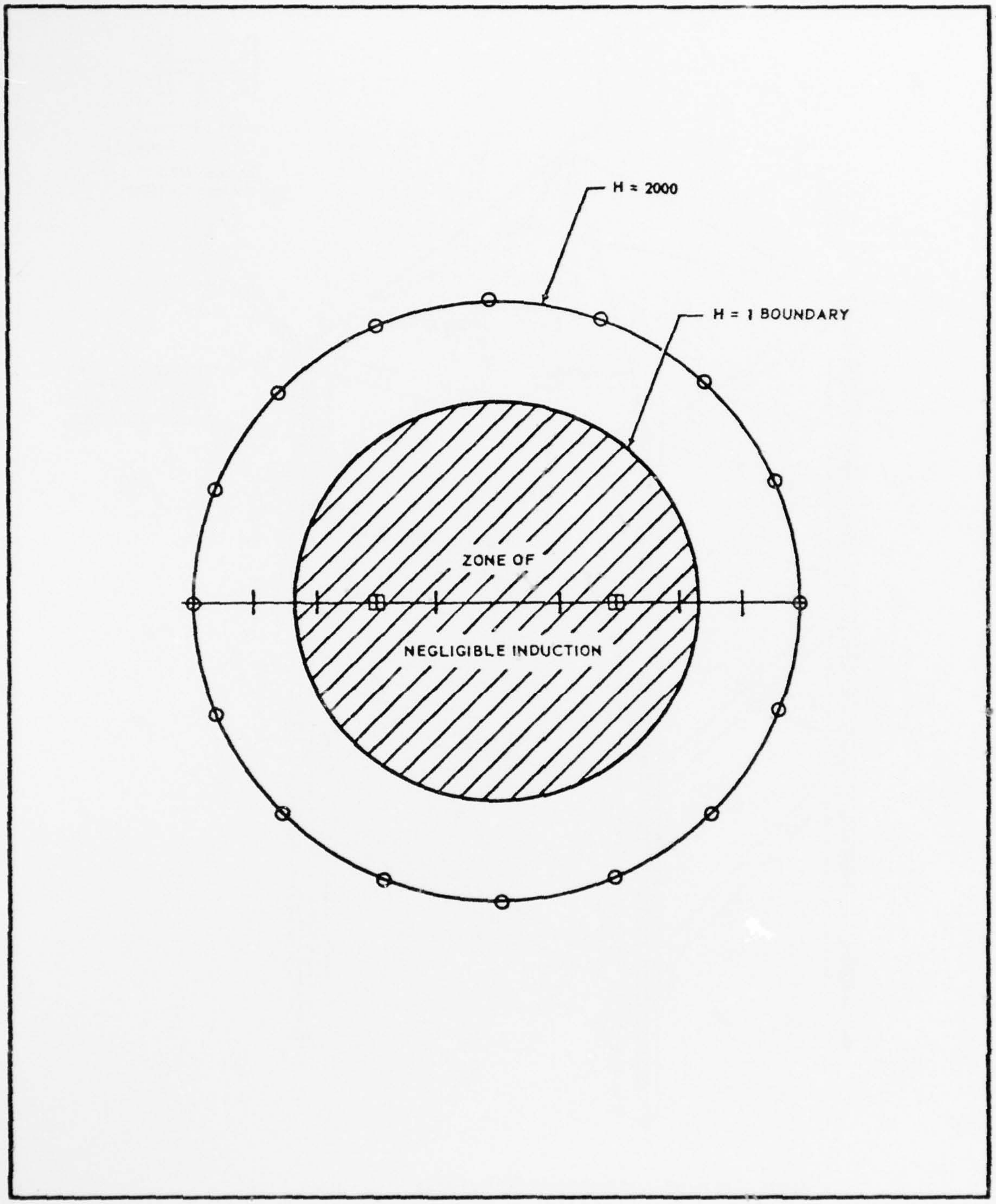

Figure 5. The Field Intensity is Reduced From 2000 Ampere/Meter Between The Wires to 1 Ampere/Meter or Less for a Large Internal Region

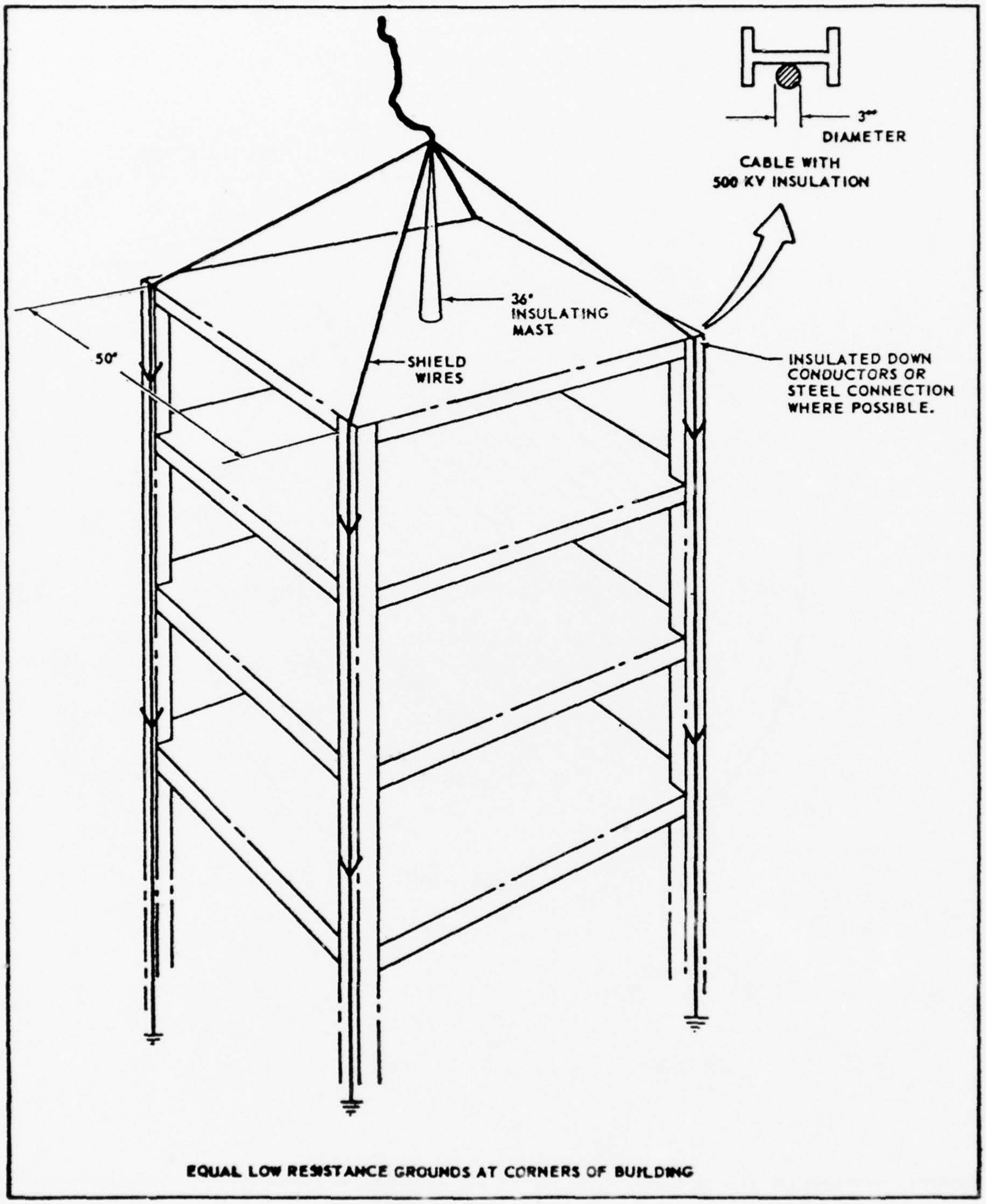

Figure 6. Controlled Symmetrical Current Flow Obtained by Using Insulating Mast and Building Steel or Insulated Conductors Grounded at the Bottom

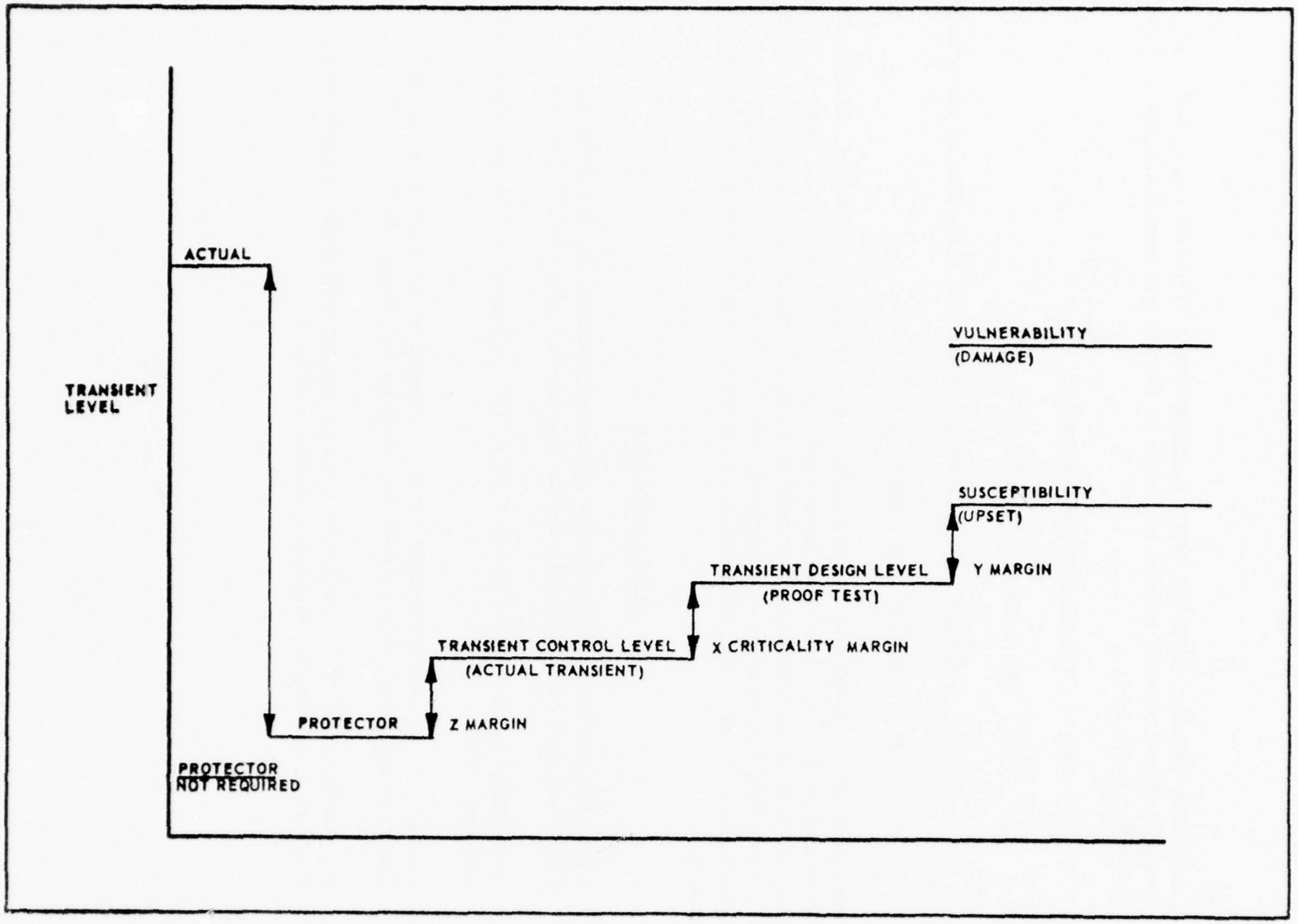

Figure 7. Control and Design Levels (Verify by Analysis and Test)

Analysis usually requires some assumptions. Therefore, proof tests of lightning induced effects should be made to verify and assist analysis. Some reasons for tests are:

a) Verification of analysis

b) Extension of analysis

c) Identification of weaknesses and detection of surprises

d) Quality assurance

Proof testing, by applying typical lightning currents to systems, is often faster and more cost-effective than analysis. Generally, it is best to combine analysis and proof testing. Periodic testing for maintenance is also desirable to ensure that the system shielding or other lightning protection has not been degraded due to environmental factors, modifications, retrofits, or other causes.

REFERENCES

1. *Lightning Protection for Saturn Launch Complex* 39, General Electric, KSC Contract NAS-410-20-13-22, September 10, 1963, Section 4.

2. DNA EMP Awareness Course Notes, IIT Research Institute, DNA 2772T, August, 1971.

3. Fisher, F.A. and Martzloff, F.O., Transient Control Levels, IEEE PES Summer Meeting, San Francisco, California, July, 1975.

4. Proceedings of 1975 Conference on Lightning and Static Electricity, Culham Laboratory, England, April, 1975.

GEOMETRIC MODELS FOR STUDY OF THE ELECTRICAL EFFECTS OF LIGHTNING

by

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When one is studying the electromagnetic effects of lightning it is frequently difficult to treat the problems analytically, even if all the factors that influence the effects can be visualized. One of the tools that may be used to aid the analysis or visualization is the geometric model; a model that is (usually) smaller than the actual system under study. By injecting lightning like pulses of current into such a model and measuring the resultant circuit behavior the investigation can frequently sift out the factors that are of most importance for further study and simultaneously identify those factors that do not significantly affect the system response.

Models are probably most valuable for their educational capabilities. They are best used for illustrating the physical phenomena involved in a lightning interaction problem and for scoping out the magnitude of the problem. Physical scaling laws and the skill of the model builder often preclude the determination of the exact response, particularly if the response involves the electromagnetic fields internal to a structure.

The purpose of this paper is to give some specific details on how models may be built and tested and to give guidance on what they can and cannot be used for.

Introduction

When one is studying the electromagnetic effects of lightning it is frequently difficult to visualize the factors that must be taken into account. It is even more difficult to treat those factors analytically. This is particularly true if the system under study is physically large because one must then take account of the distributed nature of both the electromagnetic fields produced by lightning and of the electrical circuits that are acted upon by those fields. One of the tools that can aid the investigator is the geometric model; a model that is (usually) physically smaller than the actual system under study. By injecting lightning like pulses of current into such a model and measuring the resultant circuit behavior the investigator can frequently sift out the factors that are of most importance for further study and simultaneously identify those factors that do not significantly affect the system response and which may be consigned to a guarded limbo. Sometimes the characteristics of the models are such that actual quantative measurements can be made. More frequently however the limitations of the model art (and it is largely an art) are such as to limit one to only qualitative measurements. Even qualitative measurements however can be most educational. Frequently the educational insights provided by measurements on simple models are the most valuable product of the model art.

The purpose of this paper is to illustrate some of the characteristics of models and to illustrate the uses to which models may be placed. Many of the points will be illustrated by reference to a model study made on the launch facilities used at Kennedy Space Center for the Apollo and Skylab programs. These will be supplemented somewhat by examples of models that have been used for study of the effects of lightning on power transmission lines. The treatment will be largely in how-to-do-it format; at least within the confines of one paper.

Types of Models

The type of models we will talk about the most is of the geometrical relative type. Before it is described any further, a brief digression will be made to describe other types of models used in the investigation of electromagnetic and transient phenomena.

Models are classified both as to their structure and to the information they yield. One structural type would be the model circuit in which the inductances, capacitances, and resistances of an extensive electrical system are replaced by the lumped inductances, capacitances and resistances of an electrical circuit in the laboratory. Such a model, though it may not look like the real thing, can duplicate the essential electrical quantities in which one is interested. Another structural type would be the scale model or geometrical model of which the model train is an excellent example. Such models can be made as much

like the real article as the situation warrants or as the skill of the model maker will allow.

With regard to the information obtainable from models, they can be divided into two groups; the absolute model and the relative model. In the absolute model the power level of the original is simulated and quantitative data can be obtained on all the electromagnetic properties of the system. In the relative model on the other hand, the power levels are not simulated and data can be obtained only on those properties which do not depend on power levels. These include impedances, voltages between points, current distributions, and magnetic fields in the region surrounding the model.

The type of model which is most suitable for the study of transient and electromagnetic field phenomena is the geometrical relative type.

Models are described in terms of scale factors; the relationship between a certain property on the model and the corresponding property on the prototype. These scale factors involve the fundamental physical dimensions of length, mass, time and charge (or current). Only a limited number, usually three, of these scale factors may be chosen independently. Table 1 shows the scaling relations that would apply in terms of the length (ℓ), time (t) and impedance (Z) paramenters. When scale factors are applied to these three quantitites (or any three quantities) the scale factors for all the other quantities are fixed. Care must be given to the choice of scale factors since some choices lead to more useful models than do other choices.

Models of the type we are discussing here were first used extensively for the study of lightning effects on power transmission lines. In such studies it is appropriate to choose scales such that impedances in the model are the same as the impedances in the actual transmission line. Accordingly the impedance scale factor Z is set equal to unity. Since it is most easy to work in a medium (air) having the same dielectric constant as an actual transmission line, the appropriate scale factors to choose arbitrarily are:

$$\ell = 1$$

$$Z = 1$$

$$\varepsilon = 1$$

This choice results in the length (ℓ) and time (t) scales being the same. Typical scale factors used in transmission line studies have been $\ell = 1/50$ and $t = 1/50$. With the length and time scale both equal to 1/50 other scale factors are as shown in Table 2. All these relationships can be met except the requirement that conductivity in the model be 50 times that in the actual structure. Materials with a conductivity 50 times that of structural steel, aluminum or copper do not exist. This is unfortunate, but merely reflects the fact that modeling

requires that compromises must be made between the demands of theory and the limitations of practice.

The problems raised by material conductivity set one of the important dividing lines between what models can and cannot be easily used for. Broadly speaking, if the effects under study are influenced by the electromagnetic fields external to the materials from which the model is made, the models may be used for quantitative studies of electrical response. Transmission line studies fall into this category. The voltages induced on conductors are influenced very little by the material from which the towers are built and so theoretically correct scaling of material conductivity is of little importance.

Studies involving electromagnetic fields internal to a structure produced by an external source are a different matter. Such fields are strongly influenced by the electromagnetic shielding properties of the material, properties strongly dependent upon material conductivity. We will touch only very briefly on the tricks available to the user of the models. As an example, it is possible to choose conductivity

$$(\sigma = \frac{1}{\ell Z})$$

as one of the three quantities to be chosen independently. If the impedance (Z) and the dielectric constant (ε) are chosen to be unity then the length and time scales should be chosen as $\ell = \ell$ and $t = \ell^2$. This course of action has the drawback that the time scale may become too small to handle. On a 1/50 scale model the time scale would be 1/2500. To duplicate a 1 microsecond rise time source current would require a model source rise time of 400 picoseconds. Alternatively one might build a model from thinner materials than the length scale would call for.

Frequently the manual dexterity of the model maker, or the cost of buying his services, sets more of a limitation on the construction of the model than does the availability of materials from which to build the model. Under those circumstances there is some virtue in ignoring the subleties of modeling and using the model primarily as an educational tool.

Construction of a Typical Model

Perhaps the easiest way to illustrate the potentialities of models is to describe one model that the author has used. It was a model used to verify some of the assumptions made during an analytic study of voltages induced on electrical wiring of Apollo type launch facilities at Kennedy Space Center. As such, this model was intended mostly as an educational tool and not as an exact duplication of any specific launch facility.

The model was constructed to a length scale of 1/48, 1" on the model corresponding to 4' on the actual launch facilities. To all intents and purposes this can be taken as a length scale

of 1/50, a more numerically convenient value to use when discussing test results.

A photograph of the model is shown on Figure 1. Only one swing arm was simulated since the purpose of the tests was only to demonstrate some of the basic principles of transient voltage generation, and not to obtain qualitative data on circuits that were used in Skylab or Apollo.

Some characteristics of the model are as follows: No attempt was made to duplicate the type of materials used in the actual launch facility or to duplicate the exact cross-sectional shape of the structural members. The legs of the tower were made from aluminum angle, the diagonal bracing members made from aluminum rectangular strip and the decks of the tower made from galvanized steel folded into the shape of a shallow dish. The base was formed from galvanized steel shaped into a box structure. The tops and bottoms of the base were bolted onto the sides of the base with machine screws at 2" spacings. The walls which outlined the openings through which engine exhaust would pass were likewise formed of galvanized steel, bolted to the top and bottom plates. No attempt was made to duplicate the partitions or floors internal to the base. Within the tower the elevator shafts were duplicated by a rectangular box of galvanized steel extending from the top to the bottom of the tower. A number of the cable trays running vertically in the tower were duplicated, the trays being duplicated by 1/4" copper tubing passing through the various floors and making a press fit with the floors. Where the cable trays opened into the base the copper tubes were soldered to the galvanized steel top plate of the base. No attempt was made to duplicate stairs or any of the water, propellant, or air conditioning pipes that were present on the actual launch facility.

A vehicle was simulated by an aluminum tube. The bottom of the vehicle was open. The top could be covered by a metal sheet held in place by a weight. Any more detailed simulation of the vehicle would have been a waste of time since the purpose of the simulation was only to provide a check on some of the assumptions upon which analytical studies were based.

A limited number of dummy electrical circuits were run from the base, up the cable trays and across the umbilical arm to the vehicle. These circuits will be described in a bit more detail later on.

Test Techniques

The equipment and techniques required to inject lightning-like currents into the model and to measure the resulting currents, voltages and magnetic fields will be described in considerable detail with the aim of presenting "how to do it" information to others that may wish to pursue the model art.

The first point to emphasize is that the model was not subjected to high voltage arcs from any high voltage laboratory generator. Rather it was subjected to current impulses

conducted directly into the model from a low voltage pulse generator. Low voltage is used in a relative sense here; charging voltages in the pulse generator had to be upwards of 15 kV in order to inject sufficient current into the model that measurements of voltage on representative shielded circuits could be measured. Such charging voltage and pulse power levels are well beyond the range of any typical laboratory pulse generators, even those billed as high power pulse generators.

The reason that one needs a high voltage for the generator is that the current into the model must be built up to substantial levels in a fairly short time, 1/50 the time for the rise of the actual lightning currents. If one is to duplicate a lightning current rising to crest in 5 microseconds the current injected into the model must rise in 5/50 or 0.1 microseconds. The rate at which current builds up in this type of circuit depends upon the ratio of the inductance of the loop through which the current flows to the resistance in that loop. That resistance may be quite high. In this particular circuit the discharge resistance was 300 ohms. The energy storage capacitor had to be charged to about 12000 volts to get the 21 amperes peak current ultimately reached.

The model was set up in a room having a floor covered with aluminum foil which was connected to the steel framing beams of the building. These beams were in turn connected to the steel plates forming the ceiling of the room. The aluminum foil provided a good ground plane. The pulse generator was placed on the ceiling above the model and connected to the model through a piece of wire. The return current from the floor back to the generator flowed in a broadly distributed manner through the steel framing members of the building. This type of connection avoids the higher inductance that would appear if one tried to provide a dedicated wire return path. It also minimizes the magnetic fields associated with the flow of current in the return path.

The circuit diagram of the pulse generator is shown on Figure 2, with the component values shown on Table 3. Capacitors C1 and C2 (in series) formed the prime energy storage capacitor. They were charged through the isolating resistor R1-R4 from an external 15 kV dc power supply. They were discharged into capacitors C4 and C5 (in parallel) through R8 and the primary discharge gap G1. C4 and C5 were subsequently discharged through the secondary spark gap G2 and into the model through L1 and R9. Spark gaps were used as the switches because they were the simplest devices able to handle the voltage. A two stage discharge circuit was used to promote fast switching of the secondary spark gap.

The layout of parts of the pulse generator is shown on Figure 3. All the parts were enclosed in an 1" x 17" x 3" aluminum box. The components were mounted on a piece of insulating board and insulated from the box by another insulating board. The primary spark gap G1 was formed from two 1.5"

lengths of 3/8" steel bolt stock threaded through rectangular aluminum blocks. Between the rods was placed a piece of copper wire of 0.05" diameter. Electrically this trigger electrode was held at a voltage half-way between that applied to the electrodes of the spark gap by the voltage divider R5-R6. A door knob-type ceramic capacitor insulated the trigger electrode from the secondary winding of the trigger transformer T1. When a pulse of about 400 volts was applied to the primary of T1 a voltage as high as 40 kV was produced in the secondary of the transformer. This voltage was sufficient to lead to a breakdown between the trigger electrode and one of the main electrodes of the spark gap. As soon as a breakdown of half the gap occurred the resulting ionization was sufficient to cause breakdown of the rest of the gap, thereby dumping the energy stored on C1 and C2 into the secondary load capacitor.

Capacitor C6, which served to filter out the high frequency noise produced by the breakdown of the spark gaps and to confine that noise within the interior of the metal case, was required to have very low inductance. C6 was physically formed from a metal plate about 1.5" wide x 5" long connected to the output terminal of the pulse generator and spaced away from the wall of the box by a piece of plastic 0.125" thick. The capacitance of C6 was thus on the order of 100 picofarads.

The waveshape of the current produced by this pulse generator is shown on Figure 4. The peak current was about 21.5 amperes and it rose to crest in about 0.03 microseconds, equivalent to 1.5 microseconds full scale. The current decayed to a half value in about 0.9 microseconds, equivalent to 45 microseconds full scale. The trigger generator, not shown for reasons of space, produced about five trigger pulses per second.

Making measurements on a model like this involves two major problems. The first is that of keeping the spurious noise (high frequency "hash") from being picked up by the measuring oscilloscope and measuring leads. The second is that of keeping the measuring leads from influencing the magnetic fields around the model or having induced in them signals noise (other than "hash") which masks the desired signals.

For control of high frequency hash it is necessary to shield both the oscilloscope and measuring cables. Ideally one would put the model inside a shielded room and the measurement oscilloscope outside, or vice versa. Such facilities were not available and so the measuring oscilloscope was housed in an aluminum box of dimensions 2' x 2' x 4'. One end of the box was open so that the operator could get to the oscilloscope and view the resulting displays. This shielding box was placed as far away from the model as possible, in this particular case about 15'. Three types of signals were brought into the oscilloscope; a trigger signal, a signal from a current measuring transformer and a signal from the base of the model.

Figure 5 shows the shielding and grounding techniques used. All the signals were carried on RG-58/U coaxial cable. The coaxial cables from the base of the model and from the current transformer were additionally shielded by 3/8" copper tubing. The tubing was fastened to the model and to the oscilloscope box with compression-type tubing fittings. Inside these tubes were placed the lengths of RG-58/U coaxial cable. At the base of the model the shield of the cable was connected to the interior side of the metal plate forming the bottom of the base. At the box holding the oscilloscope the cable passed directly through the wall of the box and went directly to the input of the oscilloscope. The coaxial cable from the output of the current transformer was treated in the same way; the cable shield being connected to the metal case holding the current transformer and isolated from the box housing the oscilloscope. The copper tube used for shielding was connected to the case of the current transformer.

The purpose of these shielding and connection practices was to minimize the noise currents that might flow on the outside surface of the shield of the cable. The less current that flows on the outside of the cable shield the less is the current that can couple from the shield onto the signal conductor inside the measuring cable. Minimizing the current on measuring cables is also the main way that one minimizes the influence of the measuring leads on the electromagnetic fields surrounding the model. An example of this is seen in the way that the input current was measured. This was done through the use of a current transformer through which the model lightning current was passed. The case of this transformer was connected carefully to the copper tube surrounding the output measuring cable. The shield, which was not allowed to touch the wire carrying the model current was run radially away from the conductor so as to most rapidly get away from the high magnetic field around the conductor. Other measuring cables were run inside the model vehicle or inside the cable trays of the tower, all places where the magnetic field was low. Some of these points will be elaborated upon more momentarily.

The oscilloscope was triggered by a signal derived from a trigger transformer around one leg of the tower. The transformer was a home-made one using three turns of wire on a ferrite core placed over the tower leg. Faithfulness of reproduction of current waveshape was unimportant here, the important thing being only to derive a triggering signal when current began to flow in the tower leg. The construction and placement of the transformer is shown on Figure 6.

Magnetic fields can be measured with a variety of pickup coils. One of these can be seen on Figure 1. This one consisted of several turns of wire contained in a shielded case. The output from this particular probe was displayed on an oscilloscope so that both the amplitude and waveshape of the field could be measured. Such a probe averages the field over a fairly large area. It is possible to make very small probes

so that detailed measurements can be made of how the magnetic field distributes around a structure. The output voltage from such probes is generally too low to be displayed on an oscilloscope, but it can be measured on a tuned voltmeter or radio interference meter. In such cases it is helpful to resonate the self inductance of the pick-up coil with a parallel capacitor and to excite the model with a CW source of that frequency. In such a case the frequency should be well below any of the natural resonance modes of the model.

Some Typical Test Results

One example of a set of measurements taken on this model is shown on Figure 7. A subminiature coaxial cable over which another shield had been pulled (making it a triaxial type of cable) was run from the base, up one of the cable trays in the umbilical tower and across the umbilical arm to the vehicle. In the vehicle it was connected to a measuring cable permanently installed in the vehicle. This measuring cable, which was also a subminiature coaxial cable, was enclosed in a copper tube run up the inside surface of the vehicle. The ends of the circuit were terminated to ground through 50 ohms, either by a resistor or by connection to the 50 ohm measuring cable running to the oscilloscope.

The inner shield could be grounded either at the vehicle (Point A) or at the base (Point B). A perennial question involves the best point to ground this shield. Measurements under all possible conditions showed that there are some significant differences in the circuit voltages depending on how this shield is grounded. Tracings of the oscillograms taken during the test are also shown on Figure 7. They show that grounding the shield at the base led to an oscillatory type of voltage that was higher than if the shield were not grounded at all. The lowest voltages were found when the shield was grounded at both ends.

A second set of measurements is shown on Figure 8. Here a singly shielded conductor was run across the umbilical arm to the vehicle. The shield represented the overall shield commonly used at KSC. The object of the measurements was to show how the grounding of this shield affected the voltage that would be produced in the vehicle. The measurements clearly showed how important it was that this overall shield be grounded at both ends. It can also be deduced from these measurements that virtually all the magnetic flux to which the conductors are exposed is that which is found around the umbilical arm.

For the purposes of this paper the important points are not so much the phenomena illustrated above, but that these types of measurements are possible and can in fact be made with relative ease once the basic model has been set up. The fact that measurements can be done directly in the time domain, rather than through the frequency domain is also important. In transient studies of this nature calculations or measurements made

in the frequency domain have the drawback that they must be converted into time domain through numerical integration of the inverse Fourier transform, a task that is time consuming and expensive without specialized and dedicated calculation equipment.

Other Applications of Models

While this paper can touch upon them only very briefly, it is appropriate to mention some of the other electromagnetic field problems for which models either have been or can be used.

The author's first extensive usage of models was to study the response of power transmission lines to lightning. Figure 9 shows how this can be done. A distributed transmission line type device representing the lightning leader was suspended above the model and charged from a voltage source. The electrical charge stored on this "leader" sets up an electric field that attracts charge of opposite polarity onto the line conductors. When the switch is closed the charge in the leader flows into the tower and sets up a magnetic field between the tower and the conductors. Simultaneously the charge on the conductors is released. The resulting voltages between the conductors and the tower can be measured with the voltage dividing probe. The switch in such a circuit can be a relay with mercury wetted contacts, an avalanche transistor or a pressurized spark gap depending on the operating voltage. This type of circuit has been used to produce current pulses with rise times on the order of 1 ns.

Models of aircraft can be used to measure the magnetic field distribution on the surface of the aircraft if lightning current passes through the aircraft. A metallic model of the aircraft would be built, suspended well away from any metallic walls or floors and current passed through the aircraft. The magnetic field intensity could be measured directly with the aid of a magnetic field probe.

In some cases tethered balloons are used to lift electronic packages to high altitudes. If they are struck by lightning significant currents can flow upon the cables interconnecting the various electronic packages. A model can be used to find out the approximate magnitude of these currents.

During the design of the Space Shuttle a question arose as to the magnitude of the current that would flow on the cables of the engine controller if the exhaust bell of the engine were struck. A very simple model of an engine was built from sheet metal. Upon this were mounted metal boxes representing the various parts of the engine controller. Current was injected into the model and measurements made of how this current distributed among the various interconnecting cables.

A variation of the model shown on Figure 1 has been used to study the effects of the lightning diverting wires used on the Skylab program and which will be used on the Shuttle. With such a model it is very easy to measure how much current flows down

the diversion wires and to measure how that flow of current reduces the magnetic field in and around the launch complex from what that field would be if the stroke were to strike directly upon the umbilical or access towers. This same model has been used to measure the current that would flow on the cables between the tail service masts and the orbiter. The measurements have confirmed that the currents and circuit voltages should be much less than they would be if an Apollo type of umbilical cable across an umbilical arm had been used. Previous, though less detailed, models had, incidentally, been used to illustrate how the magnetic fields associated with those currents led to the flow of current on the umbilical cables and to show how the placement of those cables on the arm affected the current on the cables.

Summary

Models are probably most valuable for their educational capabilities. They are best used for illustrating the physical phenomena involved in a lightning interaction problem and for scoping out the magnitude of the problem. They are also very useful as base cases against which analytical tools may be checked. They are less valuable for parametric studies in which one is looking for an optimum combination of devices or practices to minimize a particular transient problem. This is particularly true if one is working at the limits of the model art, as one is doing if the currents, voltages, or fields under study are a small fraction of the injected model lightning current or of the field produced by that current. One is likewise working at the limit of the model art if the phenomena under study are strongly influenced by the properties of the material from which the model is made. Parametric studies are best done with the aid of an analytical model developed after consideration of the phenomena revealed during a model study.

As an oversimplification one might say that model measurements are gounded in reality, but may have inconsistencies depending upon the skill of the model maker. Analytic calculations on the other hand will be consistent from one calculation to the next, but can be consistently wrong unless the calculator knows which physical factors to emphasize in his analytic models.

In general, it is easier to measure the division of current among the conductors of a model than it is to measure magnetic fields or voltages. Finally it might be noted that current division can often be measured with sufficient accuracy on quite crude models.

TABLE 1
SCALE FACTORS IN A RELATIVE GEOMETRICAL MODEL

Quantity	Scale Factor in Terms of ℓ, t and Z
Length	ℓ
Time	t
Impedance	Z
Conductivity	$\alpha = \frac{1}{\ell Z}$
Dielectric Constant	$\varepsilon = \frac{t}{\ell Z}$
Permeability	$\mu = \frac{t}{\ell Z}$
Frequency	$f = \frac{1}{t}$
Angular Frequency	$\omega = \frac{1}{t}$
Wavelength	$\lambda = \ell$
Phase Velocity	$Vo = \ell/t$
Propagation Constant	$\gamma = 1/\ell$
Resistance	$R = Z$
Reactance	$X = Z$
Capacitance	$C = t/Z$
Self Inductance	$L = tZ$
Mutual Inductance	$M = tZ$

All scale factors are of the form $\frac{\text{model dimension}}{\text{prototype dimension}}$

TABLE 2
SCALE OR FACTORS APPROPRIATE TO A MODEL WITH UNITY IMPEDANCE LEVEL

Impedance
- Impedance = $Z = 1$
- Dielectric Constant = $\varepsilon = 1$
- Permeability = $\mu = 1$
- Area = $L^2 = 1/2500$
- Volume = $1/125000$
- Inductance = $tZ = 1/50$
- Capacitance = $t/Z = 1/50$
- Resistance = $Z = 1$
- Conductivity = $1/\ell Z = 50$

TABLE 3
PULSE GENERATOR - COMPONENTS

C_1, C_2	-	0.068 μF - 10 kV
C_3	-	300 pF, 40 kV Ceramic
C_4	-	0.001 μF - 10 kV
C_5	-	0.00047 μF - 10 kV
C_6	-	Copper plate 1.5" x 5" spaced 0.125" from chassis by Lexan insulator
G_1	-	Primary Spark Gap
G_2	-	Secondary Spark Gap
P	-	Ceramic Preionizer
R_1-R_4	-	0.56 Meg, 10%, 2ω Carbon
R_5-R_6	-	100 Meg, 2ω, 10 kV
R_7	-	300Ω, 10ω Wire Wound, Non-inductive
R_8	-	150Ω, 10ω Wire Wound, Non-inductive
R_9	-	300Ω, 10ω Wire Wound, Non-inductive
L_1	-	Approx. 0.5 μH
T_1	-	TR-180B (EG&G)

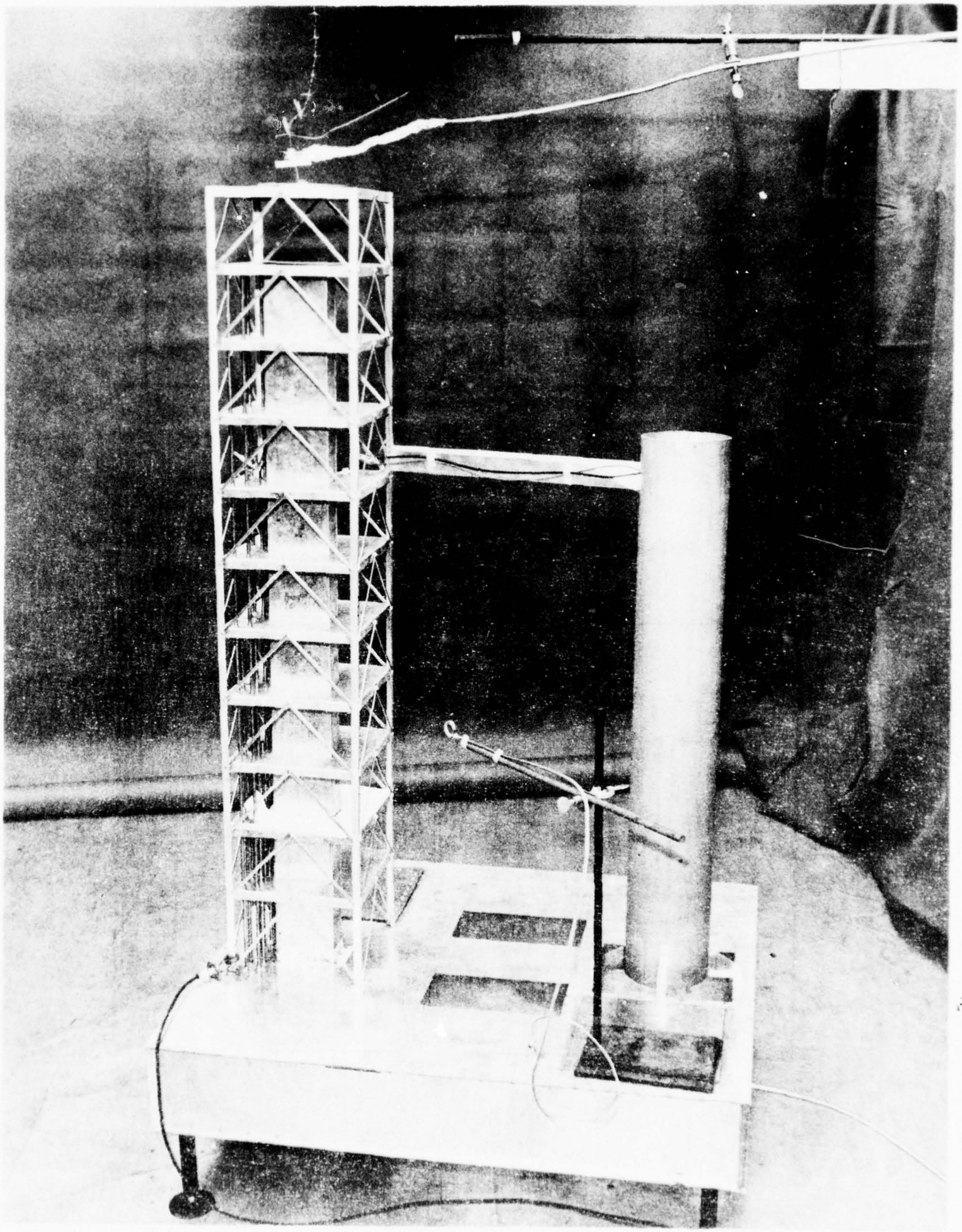


Figure 1 - A 50:1 Model of a Launch Facility.

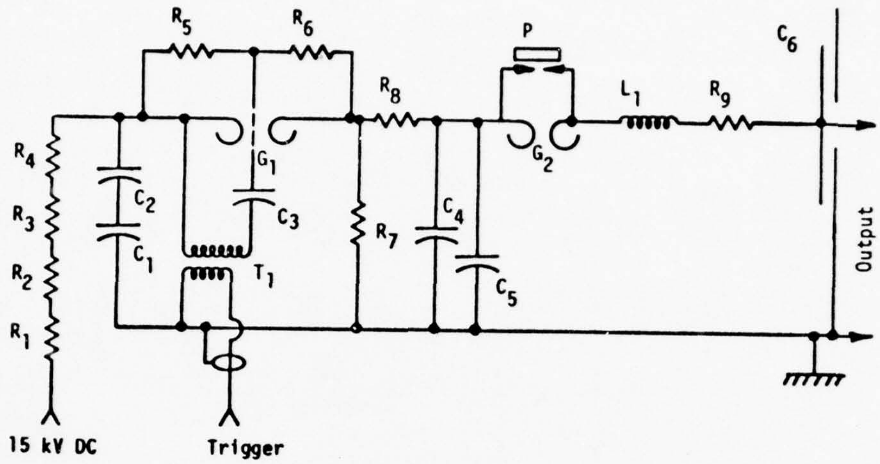


Figure 2 - Pulse Generator for Simulated Lightning Currents

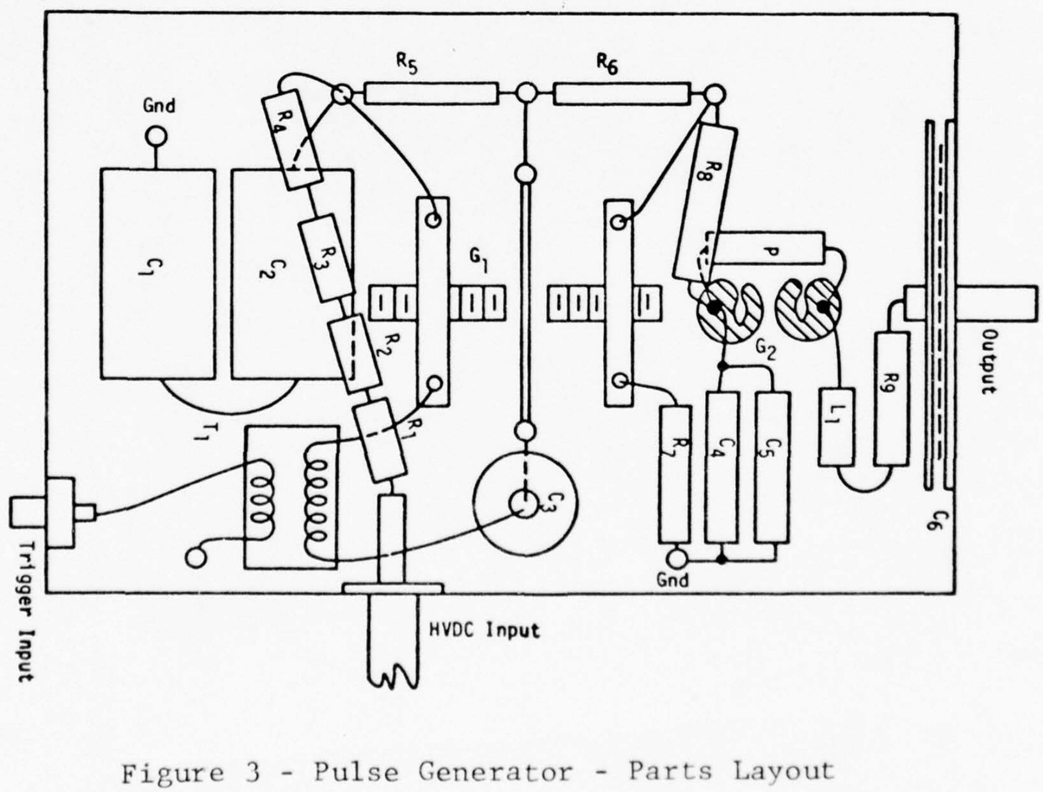


Figure 3 - Pulse Generator - Parts Layout

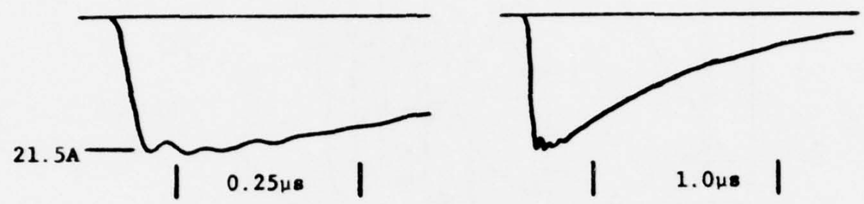


Figure 4 - Waveshape of Current Pulse

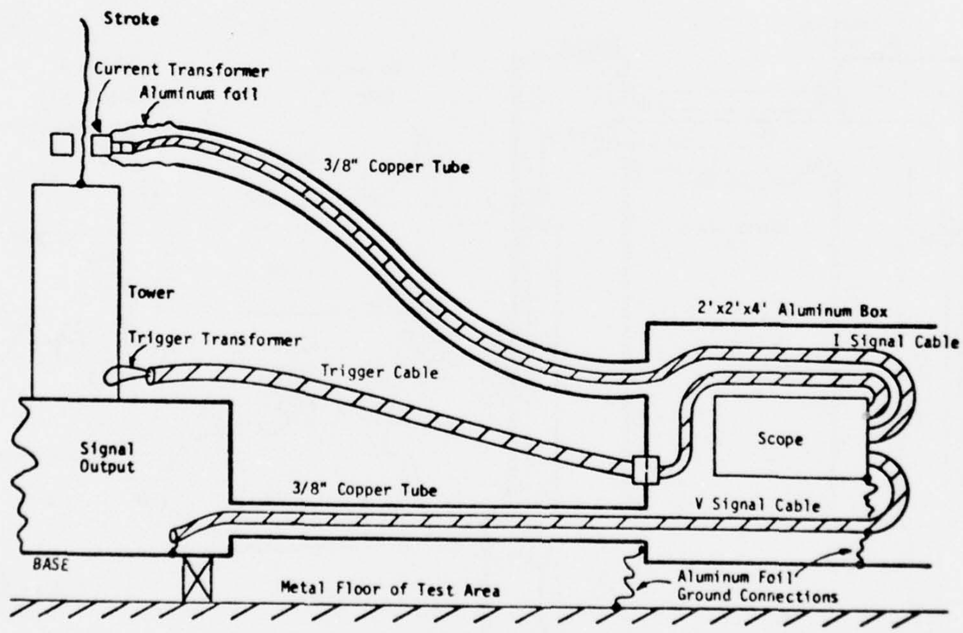


Figure 5 - Shielding and Grounding Techniques to Minimize Electrical Pickup.

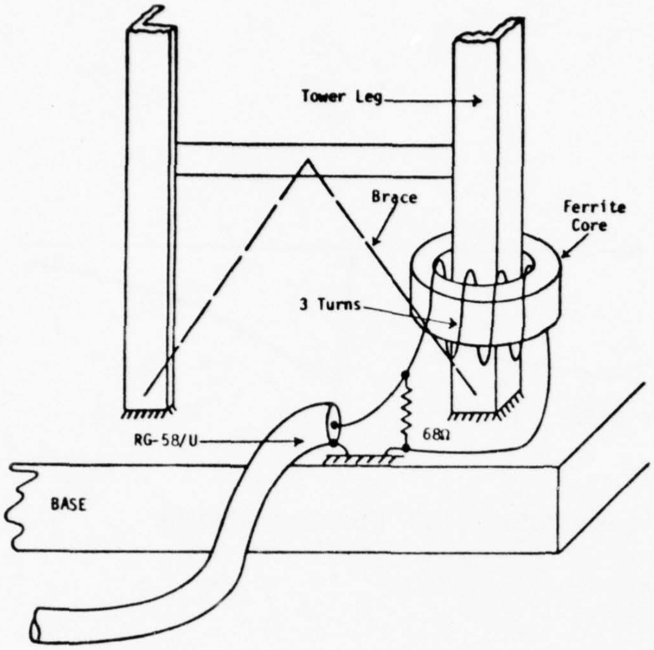


Figure 6 - How to Derive a Trigger Signal.

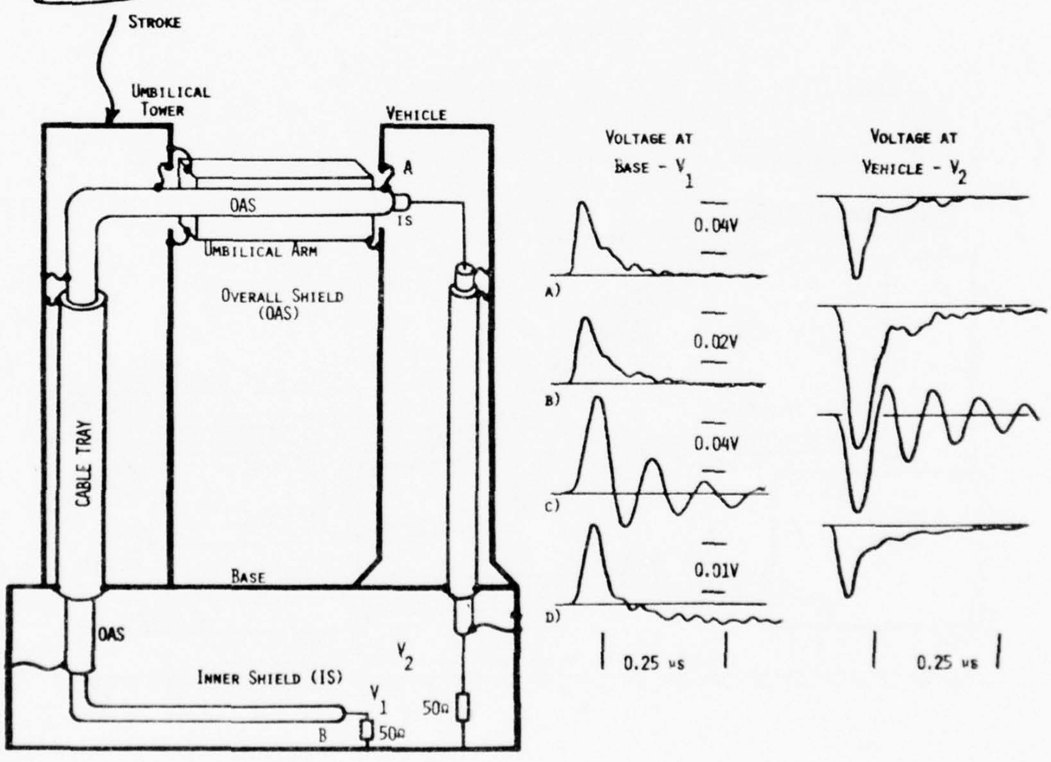


Figure 7 - Voltages Produced on a Doubly Shielded Circuit

a) IS ungrounded
b) IS grounded only at Vehicle - Point A
c) IS grounded only at Base - Point B
d) IS grounded at both A & B

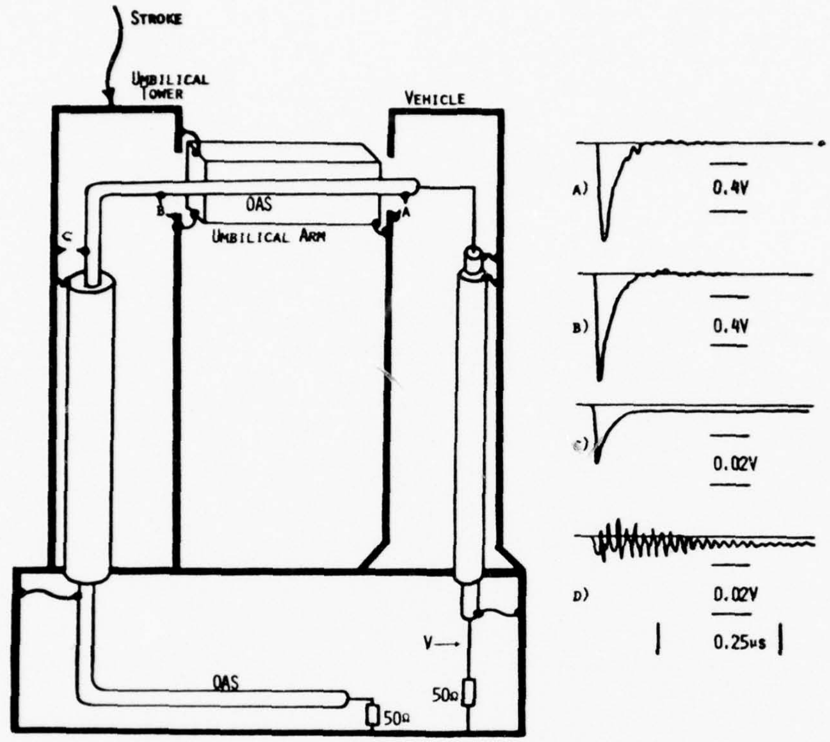


Figure 8 - Voltages on a Singly Shielded Circuit

a) OAS ungrounded
b) OAS grounded at B&C, not at A
c) OAS grounded at A,B and C
d) OAS grounded at A, not at B&C

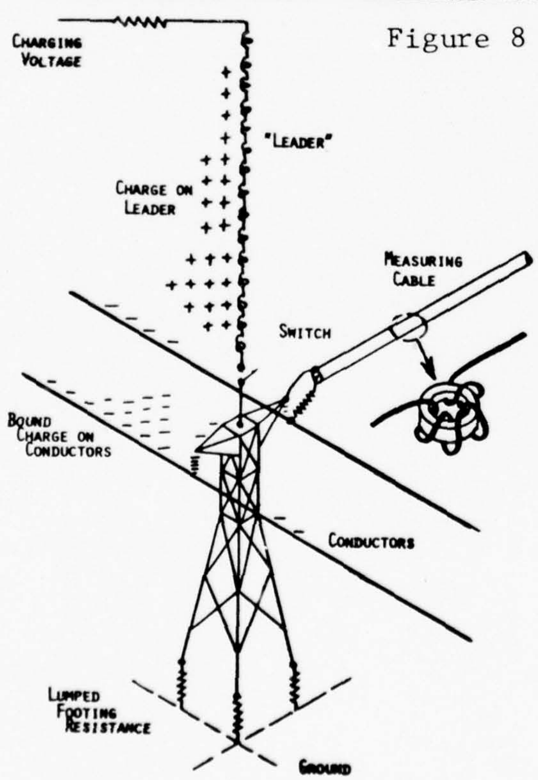


Figure 9 - A Model Test of a Transmission Line

Insert shows a balun device to prevent current flow along the exterior of the measuring cable.

LIGHTNING PROTECTION FOR

LANDLINES AND SECONDARY AC POWER LINES

(LIGHTNING PROTECTION FOR SECONDARY AC POWER LINES)

by

Lewis Becker

Kentron Hawaii, Ltd.

Dallas, Texas

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

The criteria and methodology used to determine requirements and select devices to protect systems and equipments from lightning transients conducted by landlines and ac power lines are presented. The magnitude, rise time and duration of lightning transients and surges expected are reviewed. Typical equipments and systems are analyzed to define their surge withstand capability. The characteristics and protection capacity of three types of protection devices are summarized to aid in selection for specific applications.

LIGHTNING PROTECTION FOR LANDLINES AND SECONDARY AC POWER LINES

Lewis Becker
Kentron Hawaii, Ltd.
April 1977

Kentron has been under contract since July 1975 to design lightning protection and grounding, bonding, and shielding modifications for FAA facilities. Many FAA facilities require landlines to interconnect equipments and most all use commercial ac power. Designs for existing facilities are nearing completion; however, preparation of standards and specification requirements for new equipments and facilities is just starting. A primary objective of this paper is to encourage a cooperative effort throughout the lightning protection community in the development of lightning protection criteria and standards for new equipments and facilities.

1. Introduction

Many types of components, arresters and circuits are available for the protection of equipments using landlines and ac power lines. Protection of landlines, especially buried landlines, is more readily accomplished because of the magnitude of lightning transients is far less than on directly exposed ac power lines. Additionally, series resistors can usually be added to landline circuits to divide the transient energy between two or more suppression components.

Protection criteria for landlines and ac power lines and the transient voltage withstand levels for equipments are reviewed. The characteristics of three types of protection components and their application to protection design is then discussed.

2. Protection Criteria

For protection of equipment and circuits from lightning-induced transients in buried landlines, the transient is usually defined to have an upper peak voltage limit of 1000 volts, with a rise time of 10 microseconds and a half-peak decay time of 1 millisecond. An upper peak current limit of 500 to 1000 amperes is generally accepted for buried landlines. However, all transient parameters will vary greatly depending on many physical factors including length and characteristics of the line, degree of exposure, effectiveness of any cable or guard shielding (if any), and location (number of thunderstorm days). Adjustments in the criteria are appropriate depending on the value of equipment being protected and necessity for uninterrupted operation.

For secondary ac power lines, the surge waveshape used most often is 8 by 20 microseconds with a 10 kV per microsecond rate of rise. Definition of current levels and frequency of occurrence for lightning surges conducted to the service disconnecting means is needed in order to specify protection. Kentron is in the process of developing criteria for FAA facilities and preliminary results are presented in Figure 1.

Figure 1. Lightning Current Levels on Secondary AC Power Lines (Typical Design Criteria)

NUMBER OF LIGHTNING SURGES IN 100 YEARS AT ONE FACILITY		SURGE CURRENT RANGE AT FACILITY AC POWER SERVICE DISCONNECTING MEANS (KILOAMPERES)
HIGH INCIDENT AREA 100 THUNDERSTORMS DAYS PER YEAR	LOW INCIDENT AREA 10 THUNDERSTORMS DAYS PER YEAR	
1.3	065	100 OR GREATER
3.3	.165	75 TO 100
25	1.25	50 TO 75
125	6.25	25 TO 50
800	40	5 TO 25

3. <u>Equipment Withstand Voltage Levels</u>

For selection of protection components and devices, the transient voltage withstand level of equipments and circuit components must be known or conservatively estimated. For most equipments and circuit components, standards do not exist for lightning transient levels. Therefore, information available from manufacturers must be obtained, laboratory testing performed or conservative engineering estimates used. Limits for common types of equipments and components are provided for guidance.

- Transistors and Integrated Circuits: 2 times normal voltage.
- Diodes: 1.5 times their peak inverse voltage.
- Relays and indicating lights: 5 to 10 times normal line voltages.
- DC power supplies with step-down transformer and diode bridge: 1.5 times diode PIV rating times the transformer secondary to primary voltage ratio.
- Small motors, small transformers and light machinery: 10 times normal operating voltage.
- Large motors, large transformers and heavy machinery: 20 times normal operating voltage.

In addition to the above, capacitors are many times overlooked and unless their dielectric punch-through voltage for transients is known, limiting transients to 1.5 times the dc working voltage is recommended.

4. <u>Silicon Avalanche Suppressors (SAS)</u>

Silicon avalanche suppressors (large junction avalanche diodes) are available in 1 millisecond peak power ratings of 1.5 kilowatts and 5 kilowatts as shown in Figure 2. Many devices are available with fixed parameters that fall within the voltage and current ranges given. For example, a typical 1.5 kW suppressor will have a turn-on voltage of 6.8 volts and a peak pulse current rating of 139 amperes. In comparison, a 1.5 kW SAS which turns on at 200 volts will reach its maximum clamp voltage

of 274 volts at 5.5 amperes. As expected, for devices with the same transient power ratings, the safe transient current level is less for devices with higher turn-on and clamp voltages. SAS suppressors, within practically the same voltage range are available with 5 kilowatts transient power ratings with correspondingly higher current ratings as shown in Figure 2.

Figure 2. Silicone Avalanche Suppressors Typical Characteristics

PARAMETER	RANGE OF AVAILABLE DEVICES	
	1.5 KILOWATT PEAK POWER FOR 1 MILLISECOND (DO 13 PACKAGE)	5 KILOWATT PEAK POWER FOR 1 MILLISECOND (DO 21 PACKAGE)
BREAKDOWN (TURN ON) VOLTAGE AT 1 MILLIAMPERE	6.8 TO 200 VOLTS	6.2 TO 200 VOLTS
MAXIMUM CLAMPING VOLTAGES AT PEAK PULSE CURRENT	10.8 TO 274 VOLTS	9.6 TO 274 VOLTS
PEAK PULSE CURRENT (10 X 1000) MICROSECONDS	139 TO 5.5 AMPERES	525 TO 18 AMPERES

5. Zinc Oxide Nonlinear Resistors (ZNR)

Zinc oxide nonlinear resistors are available in a wide variety of leaded disc sizes appropriate for landlines and ac power lines. Those commonly used for landline protection are listed by Figure 3. As with SAS devices, individual ZNR's have fixed breakdown (or turn-on voltages) with a corresponding maximum clamp voltage and current. In comparison SAS devices start with clamp voltages in the 6 to 7 volt range; whereas, the breakdown voltage for ZNR devices starts at 22 volts as listed for the 10 and 14 mm disc.

Figure 3. ZNR[1] Type Devices (Leaded Disc Types) Typical Characteristics

PARAMETER	RANGE OF AVAILABLE DEVICES				
	5 MM DISC	7 MM DISC	10 MM DISC	14 MM DISC	20 MM DISC
DC BREAKDOWN VOLTAGE AT 1 MILLIAMPERE	100 TO 470 VOLTS	100 TO 470 VOLTS	22 TO 1100 VOLTS	22 TO 1800 VOLTS	100 TO 1800 VOLTS
MAXIMUM CLAMPING VOLTAGE AT MAXIMUM SURGE CURRENT	230 TO 1200 VOLTS	240 TO 1100 VOLTS	90 TO 2700 VOLTS	80 TO 4400 VOLTS	240 TO 4400 VOLTS
MAXIMUM SURGE CURRENT (8 X 20 MICROSECOND WAVEFORM)	100 AMPERES	250 AMPERES	250 TO 500 AMPERES	500 TO 1000 AMPERES	2000 AMPERES
LIFE	DEPENDS ON SURGE CURRENTS AND WAVEFORM[2]				

NOTE: [1] ZINC OXIDE NONLINEAR RESISTOR

[2] MAXIMUM SURGE CURRENT (8 X 20 MICROSECOND) CAN BE APPLIED TWICE WITHOUT INCURRING DAMAGE OR OVER STRESSING THE DEVICES

Larger size ZNR discs in 20, 25 and 32 mm sizes, packaged in a molded case with terminals are available as listed in Figure 4. These sizes of ZNR discs are used primarily for the suppression of ac power line transients as indicated by their voltage ratings.

Figure 4. ZNR[1] Type Devices (Molded Case Types) Typical Characteristics

PARAMETER	RANGE OF AVAILABLE DEVICES		
	20 MM DISC	25 MM DISC	32 MM DISC
DC BREAKDOWN VOLTAGE AT 1 MILLIAMPERE	200 TO 910 VOLTS	200 TO 910 VOLTS	200 TO 910 VOLTS
MAXIMUM CLAMPING VOLTAGE AT MAXIMUM SURGE CURRENT	525 TO 2800 VOLTS	590 TO 3200 VOLTS	640 TO 3800 VOLTS
MAXIMUM SURGE CURRENT (8 X 20 MICROSECOND WAVEFORM)	2.5K TO 5K AMPERES	5K TO 10K AMPERES	10K TO 20K AMPERES
LIFE	DEPENDS ON SURGE CURRENT AND WAVEFORM[2]		

NOTE: [1] ZINC OXIDE NONLINEAR RESISTOR

[2] MAXIMUM SURGE CURRENT (8 X 20 MICROSECONDS) CAN BE APPLIED TWICE WITHOUT INCURRING DAMAGE OR OVER STRESSING THE DEVICES.

Additionally, still larger ZNR devices are available in 55, 80 and 112 mm disc sizes. Typical characteristics for a high energy ZNR arrester for ac power line protection, designed with three 80 mm discs in parallel, is given in Figure 5.

Figure 5. High Energy ZNR Surge Arrester Typical Characteristics

SIZE:	THREE 80 MM DISCS IN PARALLEL	
POWER LINE VOLTAGE:	250V AC MAXIMUM	
DC BREAKDOWN VOLTAGE AT 1 MILLIAMPERE:	560 VOLTS	
MAXIMUM CLAMPING VOLTAGE (10 X 20 MICROSECONDS)	CURRENT	CLAMPING VOLTAGE
	10 kA	1300 VOLTS
	40 kA	1600 VOLTS
	150 kA	2450 VOLTS

Figures 6 and 7 illustrate, to approximate scale, the response of SAS and ZNR devices and their voltage rise at rated currents. Since the ZNR devices typically have higher current ratings than SAS devices, comparison of specification data for both types of devices, particularily current ratings, is necessary to optimize protection design. Response time for ZNR devices is less than 50 nanoseconds, which is adequate for suppression of lightning transients. Response time for SAS devices is faster, typically a few nanoseconds.

Figure 6. Typical Operating Curve for Silicon Avalanche Suppressor

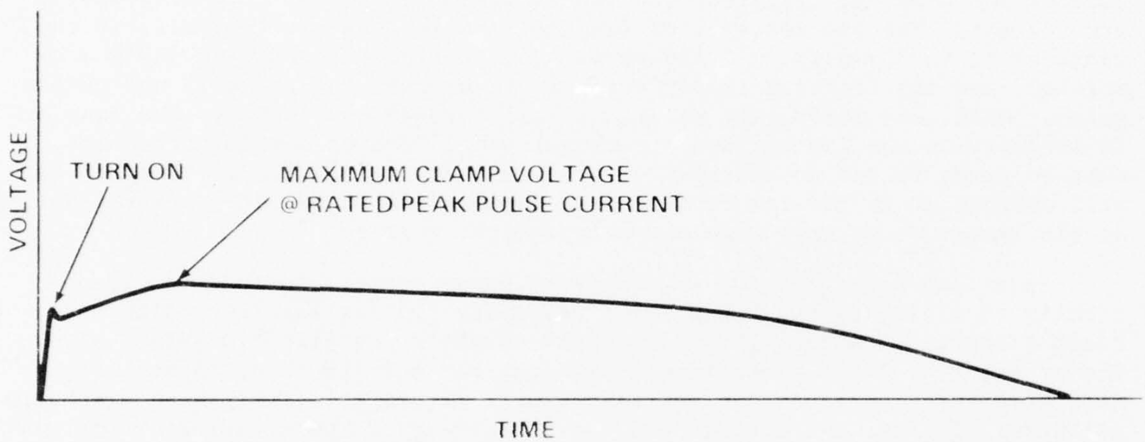
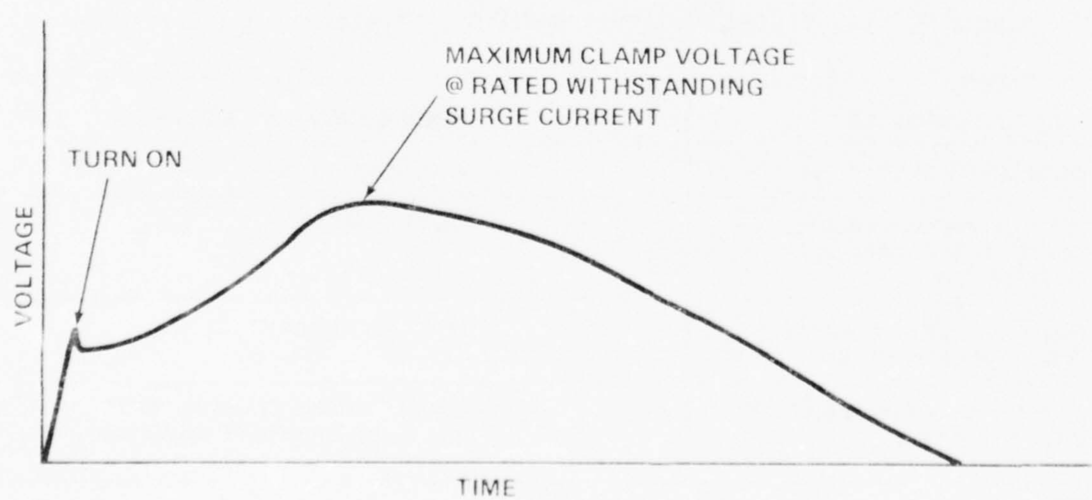


Figure 7. Typical Operating Curve for ZNR Suppressor



6. Gas-Filled Spark Gap Devices

In addition to SAS and ZNR devices, gas-filled miniature spark gaps are readily available with characteristics suitable for landline protection design. Figure 8 summarizes the characteristics of miniature spark gaps. Generally spark gaps for landlines are rated at either 5 kA or 10 kA peak current with 20 kA units available. Physical size increases with current rating and when space is available, the 10 kA size would be perferred for longer life over the 5 kA devices. The transient firing (impulse sparkover) voltage of small spark gaps typically start at 275 volts for 100 volts per microsecond rate of rise. When the impulse sparkover voltage is exceeded, the spark gap will transition to a glow mode and then to the arc mode, conduct current and drop the transient and line voltage to the gap's characteristic arc voltage. The arc voltages of miniature spark gaps are typically in the range of 15 to 30 volts. If the normal line voltage exceeds the gap's arc voltage, and the line can supply sufficient current, the gap will not extinguish. When this posibility exists, a resistor can be placed in the line or in series with the gap to insure extinguishing. During design, attention must be given to the dc sparkover rating of spark gaps. Since the spark gap will operate at dc and low frequencies, the maximum signal or operating voltages on the line must be less than the dc sparkover voltage.

Spark gap arresters for secondary ac power protection function identically to miniature spark gap arresters discussed for landlines with one basic exception. A resistive element is normally installed in series with the arrester to limit power line follow current and aid in extinguishing. With high surge currents the resistance will create relatively high discharge voltages. Typical characteristics for a secondary ac power arrester are given by Figure 9. The impulse sparkover voltage of 1400 volts is fairly representative for this class of arresters. Similarly a one-time surge rating at 150 kiloamperes and 2500 surges at 10 kiloamperes is typical. The variation in discharge voltage is illustrated in Figure 10 for surge current discharges of 10, 40 and 150 kiloamperes.

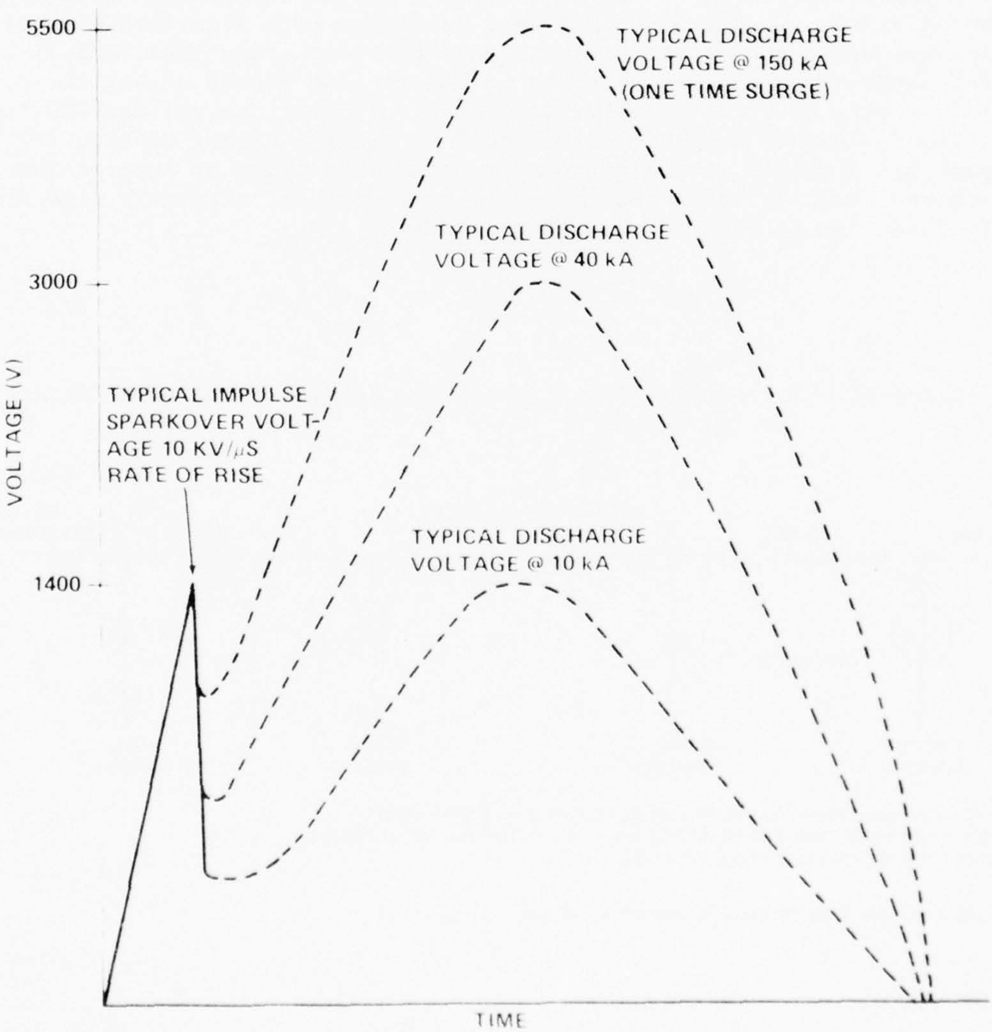
Figure 8. Gas-Filled Miniature Spark Gaps Typical Characteristics

PARAMETER	RANGE OF AVAILABLE DEVICES
DC SPARKOVER VOLTAGE	90 TO 1000 VOLTS
IMPULSE SPARKOVER VOLTAGE 100 VOLTS/MICROSECOND RATE OF RISE	275 TO 2000 VOLTS
MAXIMUM CURRENT CAPACITY (8 BY 20 MICROSECOND)	2K TO 10K AMPERES
LIFE (TYPICAL FOR SPARK GAP WITH 5 kA RATING)	50 OPERATIONS AT 500 AMPERES 10 BY 1000 MICROSECOND WAVEFORM

Figure 9. Gas-Filled Spark Gap Arrester (With Series Nonlinear Resistor)

PARAMETER	TYPICAL RATING	
IMPULSE SPARKOVER VOLTAGE RANGE 10 KV/MICROSECOND RATE OF RISE	1,400 VOLTS PEAK	
DISCHARGE VOLTAGE (10 BY 20 MICROSECOND WAVEFORM)	CONDUCTED CURRENT	DISCHARGE VOLTAGE
	10 kA	1400 VOLTS
	40 kA	3000 VOLTS
	150 kA	5500 VOLTS
MAXIMUM CURRENT DISCHARGE CAPABILITY	150,000 AMPERES, 10 BY 20 MICROSECOND WAVEFORM, ONE TIME	
LIFE	2,500 SURGES AT 10,000 AMPERES, 10 BY 20 MICROSECOND WAVEFORM	

Figure 10. Typical Operating Curve for Gas-Filled Spark Gap Arrester with Nonlinear Series Resistor



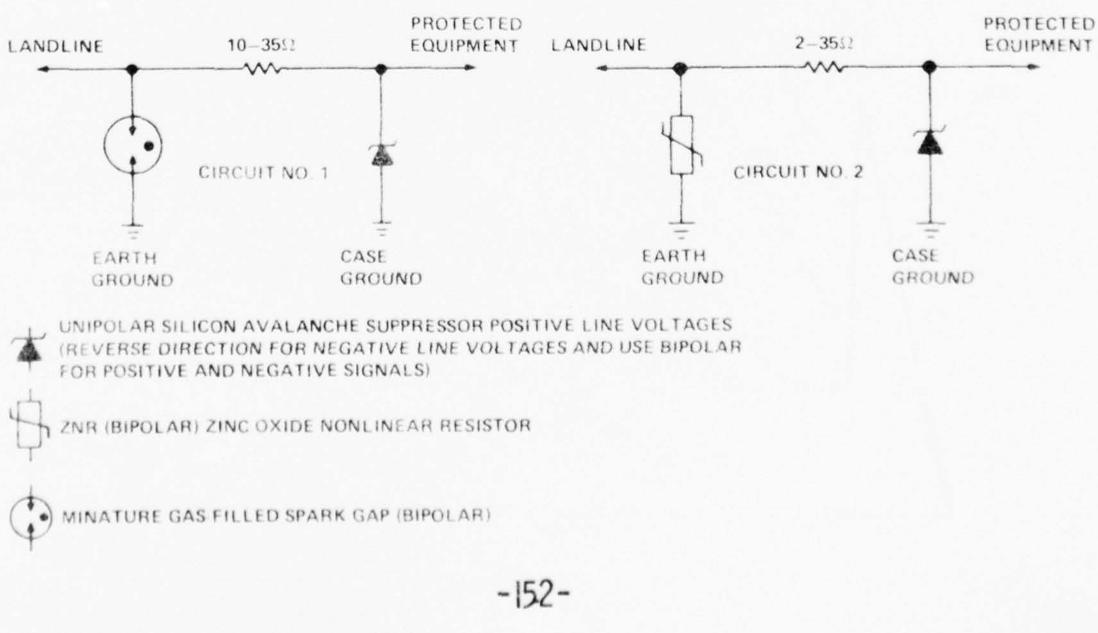
7. Landline Protection Design.

Two typical landline protection circuits are illustrated in Figure 11. These circuits illustrate the components previously discussed plus a series resistor in the line. The SAS is selected to limit the transient voltage level to below the damage level of the circuit being protected. The SAS's fast response time and long term reliable operation is used to dissipate all small surges and the initial crest of all higher surges. Higher energy surges will develop sufficient voltage across the series resistor to fire the spark gap which conducts the remaining transient current to ground.

The ZNR is an alternate device to use in place of the spark gap and particularly serves an advantage when only a low resistance can be used in series with the line. ZNR's can be selected with lower turn-on and clamp voltages, in comparison with the impulse sparkover voltages of gaps. Thus, a smaller resistor can be used to limit the current through the SAS.

The circuits illustrated are presented as typical. Many variations and alternatives exist. If the value of the equipment is relatively low and continuous operation is not essential, a single suppression component may be selected. On the other extreme, landlines with significant exposure, costly equipment, and essential continuous operation, may justify a five element suppression circuit, such as an SAS to case ground across the protected circuit, a series resistor (or inductor), a higher voltage ZNR to case ground, another series R or L, and then a still higher voltage ZNR or spark gap directly to earth ground. By the selection of suppression turn-on and clamp voltages and resistors or inductors, extremely high transient energy can be distributed and dissipated.

Figure 11. Control and Signal Landlines Typical Protection Cricuit Configurations

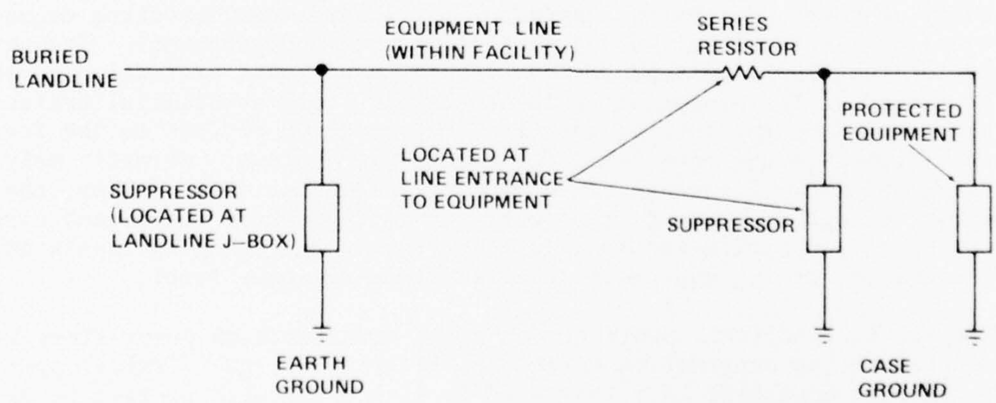


8. Landline Protection for New Equipments

Protection for equipment circuits requiring landlines is best and most economically implemented when equipments are designed. After the fact modifications for equivalent protection will invariably cost 10 to 100 times more for proper installation, documentation and drawing changes.

Typical landline protection for new equipment design is illustrated in Figure 12. The preferred location for the first suppressor is directly from line to equipment case. The series resistor (or inductor) is specified within and as part of the equipment to be certain the equipment designer accounts for the line voltage or signal drop. The ZNR or spark gap, suppressing the higher voltages, is located at the facility landline junction box to limit transient energy within the facility. Providing a short direct connection to the earth electrode system is necessary for the higher energy suppressor at the landline junction box. This is particularly important for all spark gap devices to keep the discharge current surge off equipment ground networks. Landlines should be routed separately from low level analog and digital signals within the facility. Finally, to avoid a split in responsibility between equipment design and facility design for the protection circuit components, the equipment designer should specify the suppressor for installation at the junction box.

Figure 12. Control and Signal Landline Protection
Protection Component Location (New Equipment Design)



9. AC Power Protection Design

Protection of equipments from lightning surges on power lines requires arresters and protection devices that conduct or dissipate high levels of surge energy and current in comparison with the relative low level transients expected on buried landlines. Secondary power lines to facilities are usually directly exposed to lightning and are larger (greater ampacity) than most landlines. Protection design for ac power lines is further handicapped because the addition of series resistors in the line to divide the surge energy between several devices is essentially prohibited by the drop in voltage that would be incurred.

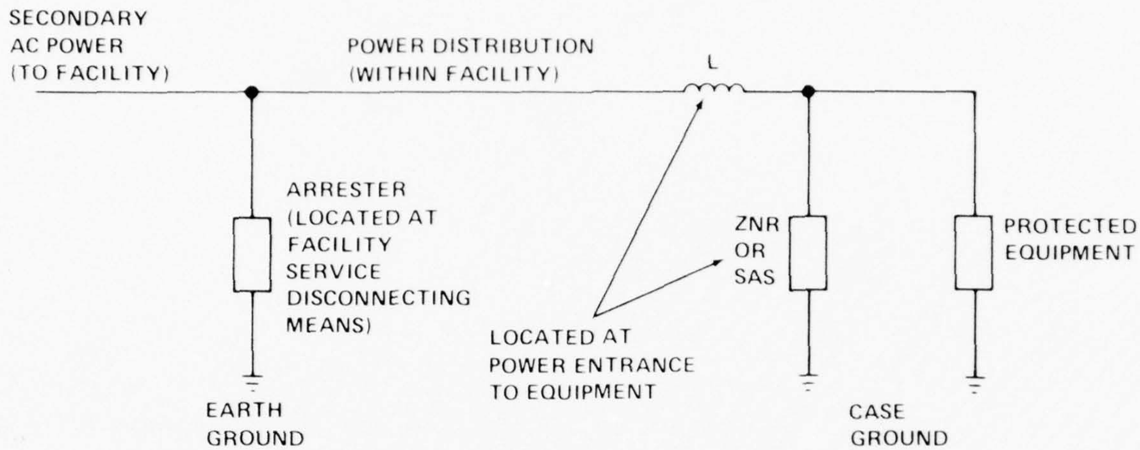
Protection design, however, can take advantage of the division and dissipation of surge energy provided by feeders and branch circuits within the facility. Division of surge energy at the service entrance will depend on the number and impedance of feeder and branch circuits. Dissipation of surges within the facility to an equipment item will occur depending upon the resistance, inductance, and distributed capacitance of feeders, branch circuits, and power line components such as breakers. Consideration of these factors explains the extensive damage which occurs frequently to equipment housed in small facilities or shelters in comparison with the relative infrequent damage to equipment in large facilities. Further analysis shows that heavy equipment such as air conditioning motors, normally installed close to the service entrance in large facilities will shunt an appreciable percentage of the surge energy conducted into the facility by the secondary ac power lines; thereby, providing a level of protection for sensitive electronic equipments which are normally further removed from the service entrance.

In effect, a paradox exists. Customarily, large facilities receive better and more costly protection for ac power lines in comparison with small facilities. Generally, equal or better protection is needed at small facilities or shelters particularly those housing electronic equipment.

During protection design the above factors need to be considered, as well as the transient levels expected at the service entrance and the susceptibility or voltage withstand characteristics of facility equipment. As a minimum, a secondary ac power arrester is needed at the service disconnecting means to dissipate high surge levels and protect equipment and personnel. For equipments with relatively low withstand voltage levels, additional protection devices may be needed at the equipment enclosure level. Very substantial protection can be provided by the further addition of protection devices to the feeder or branch circuits at the room level for electronic systems. Normally only inductors with minimum DCR ratings can be added to ac power lines. Thus, the transient voltage drop due to the power feeders, breakers and branch circuits must be closely approximated to select the turnon and clamping levels of protection devices at the equipment level and room or space level.

Similar to landlines, protection against transients on power lines is best implemented during original equipment and facility design. Typical protection for electronic equipment is illustrated in Figure 13, with protection devices at the service disconnecting means and at the equipment level. The protection illustrated at the equipment level can be improved by the addition of a second suppressor from line to equipment case ground to form a pi network. Identical protection networks or devices are necessary for both phase and neutral conductors except at the service disconnecting means where the neutral is grounded.

Figure 13. Secondary AC Power Protection (New Equipment and Facilities)



The combination of rf interference requirements with power line lightning protection design for new equipments is feasible and recommended. Most equipment designs for compliance with interference standards and test limits will include a power line filter. As a minimum, interference filters will usually have an inductor in the line with two capacitors to case ground in a pi configuration. Interference filters are designed to attenuate transients, but generally, the capacitors will be limited in comparison with the current and power rating of lightning suppressors. The specification of a combination rf interference filter and lightning suppressor for new equipment design will potentially serve to cover both requirements with minimum costs.

PROTECTING FACILITIES FROM INDUCED LIGHTNING AND POWER LINE SWITCHING TRANSIENTS BY A TOTALLY SOLID-STATE DEVICE

(PROTECTION OF COMPONENTS, CIRCUITS AND SYSTEMS)

by

Richard Odenberg

Transtector Systems

Monterey Park, California

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

For the pa^t 20 years a sing! component was used for protection of the A.C. power line from induced lightning.

With complete change over to s... -state equipment; i.e. rad..., telecommunication, computers and electronic controls, the requirement for a far better protector is needed now. It is needed not only for lightning, but from the more dangerous hazard of power line switching transient which occur from day to day.

This paper discusses the five most important technical factors when selecting protection for your facility against these two hazards. Additional consideration is made as to whether the protector is protecting only equipment or is it protecting human life?

A detailed description of an A.C. Voltage Suppressor that appears to be the Absolute Transient Suppressor for facilities. Totally a silicon solid-state device, it functions like a bipolar zener clamping the voltage, (120 vac line) at 400V peak, while dissipating 2500 joules (1 x 1000 microsecond). It's response time is less than 50 nanoseconds.

Included will be details of Installations, Specifications and results at FAA sites installed in 1971, Satellite tracking station installed in 1974, and an ADC site installed in 1975.

TRANSIENT PROBLEMS - WORLD WIDE

"The transient voltage" is probably the least understood element of electrical energy because there is very little data available on the subject. In simple terms, transients are short term overvoltages produced on the electrical line, by a number of extraneous causes which result in a momentary rise of the voltage above some predescribed threshold level. While transients have certainly been a phenomenon since the discovery of electrical energy, they have not always been a recognized problem. Until now, transients were probably not a serious causative factor in damage or down time to electrical equipment.

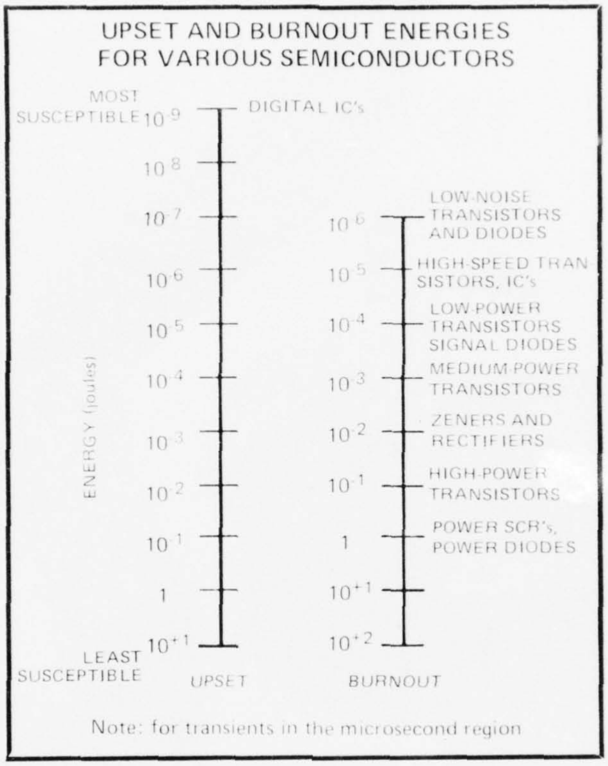
REASONS FOR IMPROVED PROTECTION

With the introduction of solid-state semiconductors and integrated circuits, there has developed a serious need for solid-state transient voltage suppression equipment, which reacts fast enough to protect very sensitive electrical/electronic equipment, against minute levels of "unexpected" energy. Previously, AC Voltage Regulators, Gas Discharge Tubes or Spark Gaps, have been sufficient to protect most vacuum tube equipment from transients; however, the solid-state components are more susceptable to very short duration bursts of energy, and therefore require a special type of protection. It is for this reason that there is an increasing need in solid-state transient protection equipment, and over the next decade, this will become the number one topic of discussion among those involved with electrical energy.

There are three (3) specific reasons for the change in voltage suppression requirements: (1) The increased effect of induced lightning on solid-state components (also enhanced by a changing world weather pattern). (2) More and more sophistication in semiconductor technology, simply smaller and smaller devices. (3) The very monumental effect of switching transients/surges caused by a degenerating supply of commercial power. As the demand upon power companies increases, at a geometric rate,

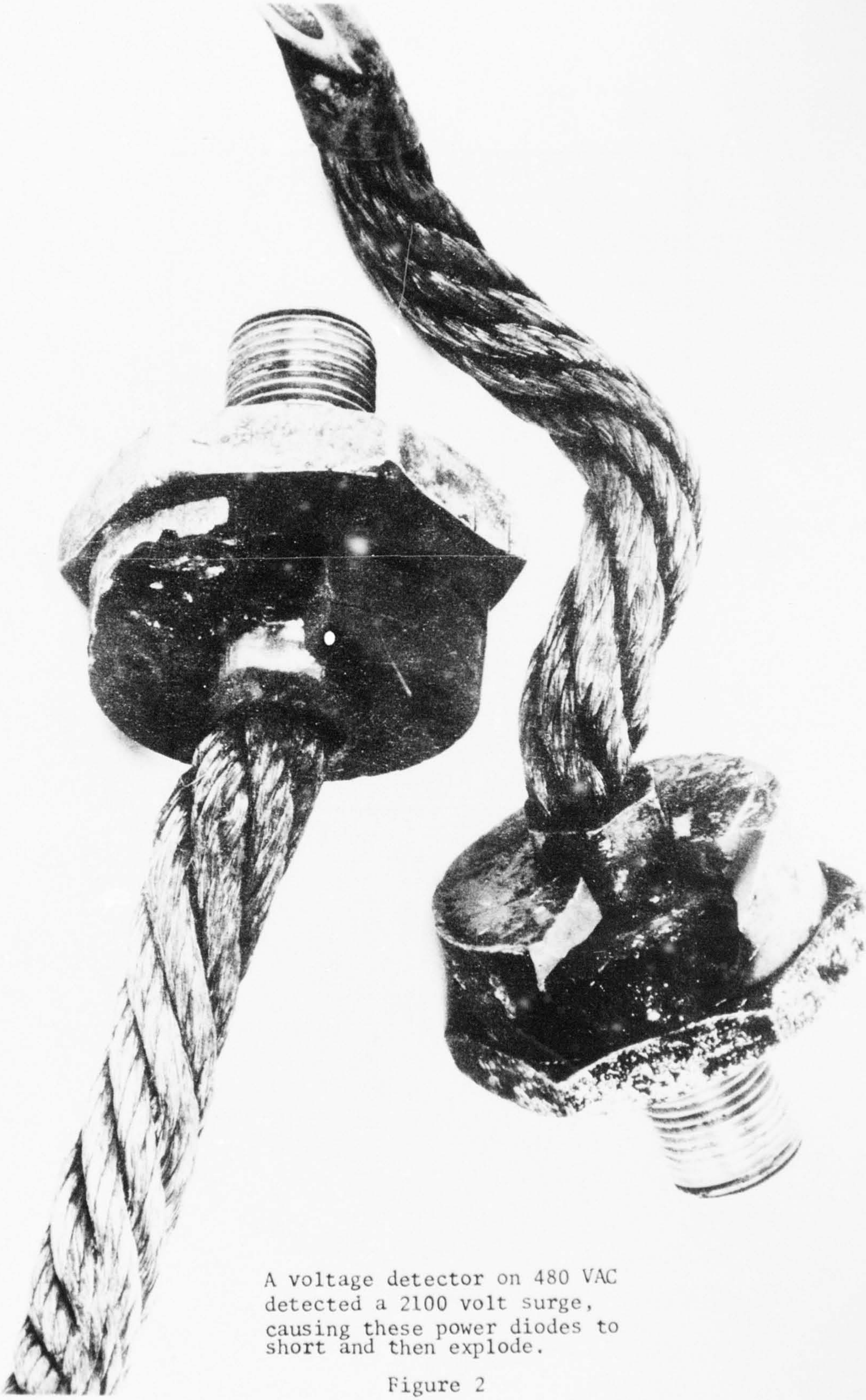
the ability to produce power does not increase at the same rate. Therefore loads are constantly being switched from one line to another, causing "surges" (which in turn, cause high speed, short duration transients to proceed down the power line). As little as 1 nanojoule (1×10^{-9}) of energy applied to the semiconductor can cause a shut down of operations. Figure 1 shows how little energy can either upset or destroy a transistor, I.C. or semiconductor. This data was developed for transients in the microsecond region. Just think, if they were 1 millisecond long (a thousand greater) what damage they might do. Figures 2 and 3, show what can happen when the transient or surge hits the semiconductor. By definition, a transient is less than 8.3ms and a voltage surge is greater than 8.3ms. Transients are also related to high impedance sources and can range from a few millivolts to 20K volts. Voltage Surges are produced from low impedance sources. In general the maximum voltage seen is 2 to 3 times the nominal operating voltage. The failure of the power diodes in Figure 2 was due to a voltage surge. The failure in Figure 3 was due to a transient.

After many years of testing and field evaluation of different devices, i.e. Gas Tube and Metal Oxide Varistors, it was found that the systems approach was the only way to meet all the technical requirements for protecting solid-state equipment. These facts came out when in many applications, hospital, air traffic control and emergency disaster conditions, meant human lives were at stake. The FAA saw this problem in the late '60s, and moved to put in solid-state surge protection then. In addition, in the early '70s , UPS Systems were put in also. In applications where human life is a consideration, one must consider technically nothing less than absolute transient suppression. Where equipment damage only, is the consideration, then the cost factors must be considered as a trade-off to the other economics such as maintenance of equipment and down time.



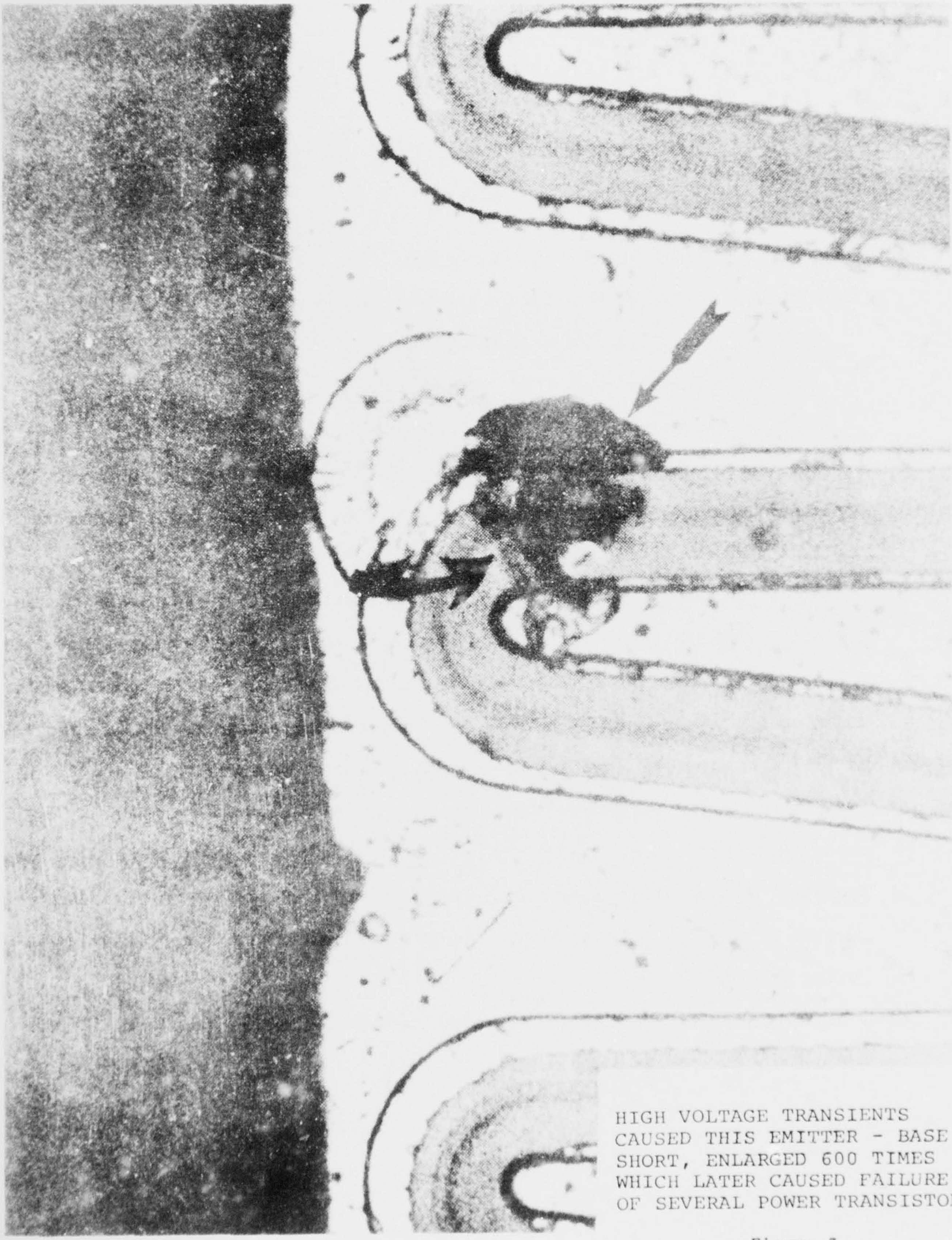
Reference: Intelcom Rad Tech
INTEL-RT-8094-013
Sept. 1974

Figure 1



A voltage detector on 480 VAC detected a 2100 volt surge, causing these power diodes to short and then explode.

Figure 2



HIGH VOLTAGE TRANSIENTS
CAUSED THIS EMITTER - BASE
SHORT, ENLARGED 600 TIMES
WHICH LATER CAUSED FAILURE
OF SEVERAL POWER TRANSISTORS

Figure 3

FIVE MAJOR CONSIDERATIONS IN PROTECTING FACILITIES AGAINST HIGH ENERGY AND HIGH SPEED ABNORMAL VOLTAGES.

1) Response Time - High speed - low nanoseconds. This is important because of the high speed rise time of the induced transients or surges.

   Lightning.......... 600V to 1000V/Microsec.

   Power Line Surges... 100V to 300V/Microsec.

   EMP (Electromagnetic Pulse).... 5KV/Nanosec.

2) Suppression (Power) Capability - 100,000 to 1,500,000 watts and capability of suppressing 15,000 to 50,000 amps, induced on the AC service line. Experience and test measurements show these energies do exist on the power line.

3) Voltage Suppression & Clamping Ratio - Low threshold and less than 1:1.5 clamping ratio. The device is to turn on, and start suppressing at 120 percent of nominal line, and at maximum power not to exceed 150 percent of nominal line, a clamping ratio of 1:1.5. If a protector does not begin to suppress at low voltage threshold it will allow the low level surges through to damage equipment.

4) High Reliability - The device should be totally solid-state, with redundant circuitry and be failsafe.

5) Operation - Automatic or Resetable. If the nature of a system precludes an interruption in service (that is, if one cannot afford to be shut down) an automatic device is required.

These basic principles were considered in the design of Transtectors' Model ACP1000 and ACP10,000 A.C. Voltage Surge Suppressors.

DESCRIPTION OF ACP10,000 & 1000 VOLTAGE SURGE SUPPRESSORS

GENERAL

The AC Voltage Surge Suppressors are high-speed, high current, solid-state devices designed to protect solid-state electronic equipment and systems from transient overvoltages. They perform their function by limiting the magnitude of the transient overvoltage present on the AC power lines at a specific peak threshold voltage. Such transient voltages occur due to the fuse clearing, phase switching, between power sources; equipment start-ups or shut-downs, switching loads and induced lightning. The ACP series are designed specifically to operate on either single, two or three phase Delta or Wye services.

OPERATION

The suppressors operate when the instantaneous voltage rises above 120 percent of the nominal peak voltage. The power dissipated in the suppressor is a function of the energy in the transient only. The suppressor does not handle available fault current of the power line, as do crowbar type circuit protectors, when dissipating the transient energy. The ambient temperature of the suppressor rises as do the suppressor voltage level. When the line voltage is below 120 percent, the device draws a maximum power of 1 watt per phase. The elements employed are 100 percent solid-state, using redundent techniques and component ratings and construction, to assure good reliability.

FUNCTIONAL

When a transient overvoltage is sensed at the suppression voltage level (on any or all phases) the suppressor on that phase, conducts in approximately 5 nanoseconds, attenuating the transient voltage and dissipating its energy. It continues to suppress until the voltage drops below the clamping level. When the transient voltage is no longer on the line or is below the clamping voltage, the suppressor automatically recovers, ready for the next transient. The suppressor is bi-polar, suppressing transients either on the positive or negative side of the sine wave. It is also bi-directional and will suppress transient voltages generated by the load as well as the source.

ACP10,000-120W - 2500 Joule Suppressor (for 120, 240 or 480 VAC Service)

MECHANICAL

The controls and power electronics are located in a Nema 12, Free Standing Enclosure, 6' x 3' x 1-1/2'. The unit weighs approximately 500 pounds. (Figures 4 and 5.)

ELECTRICAL

All functional devices are silicon solid-state. No MOV (Metal Oxide Varistors) or Gas Discharge Tubes are used in the circuits, due to their short life expectancy and lack of adequate protection for solid-state electronic equipment. In order to suppress such large currents in the nanosecond to microsecond region, there are several stages of suppression in the ACP10,000. The first stage has the capability of suppressing at 150,000 watts per phase before the second stage comes on automatically and suppresses up to the maximum rating of 1.5 megawatts (1 x 1000 microsec). Maximum voltage rise on the 120VAC unit is 400 volts peak at 1.5 megawatts. It is very important to realize that this device does not short or distort the AC line, it strictly clips the transient "off", and then automatically resets upon removal of the transient. (Summary Spec. Figure 6.)

The dynamic impedance for the suppressor, when no transients are suppressed, will be in the hundreds of thousands of ohms, but when a major surge occurs, it could be as low as .1 ohms, which gives you a substantial suppression capability of the power line.

The ACP10,000 has additional features which are: 1) Transient Simulate Test - this test triggers the suppressor by pressing a test simulate button which gates on the circuitry (note: it does not disturb the line at all) and if the suppressor triggers, it turns on lights on the front panel. The suppressor is then reset by pressing the "reset" button. This test proceedure is done on a regular basis at the site, to verify the unit is still functioning properly. 2) Digital Transient Counter - the

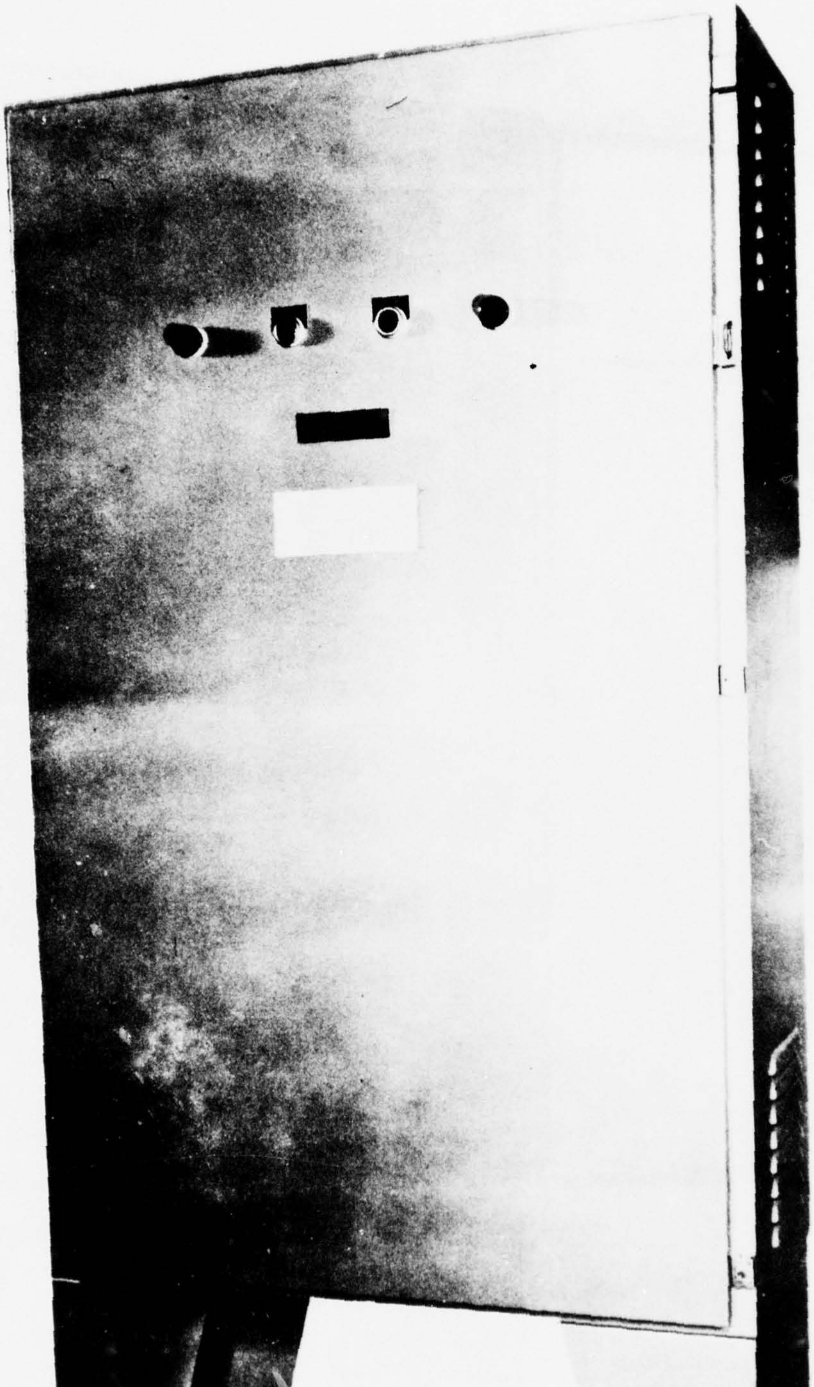


Figure 4

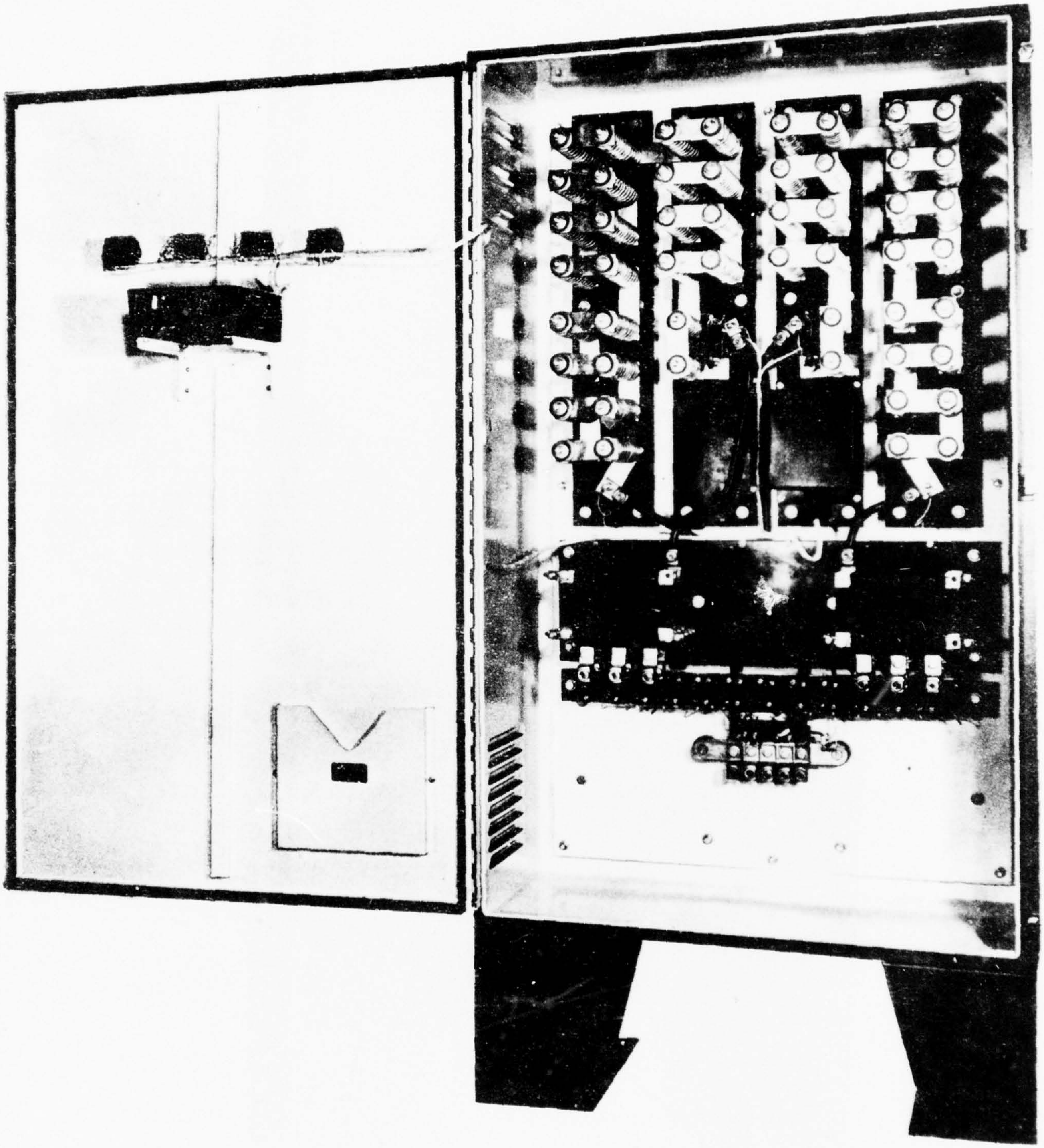


Figure 5

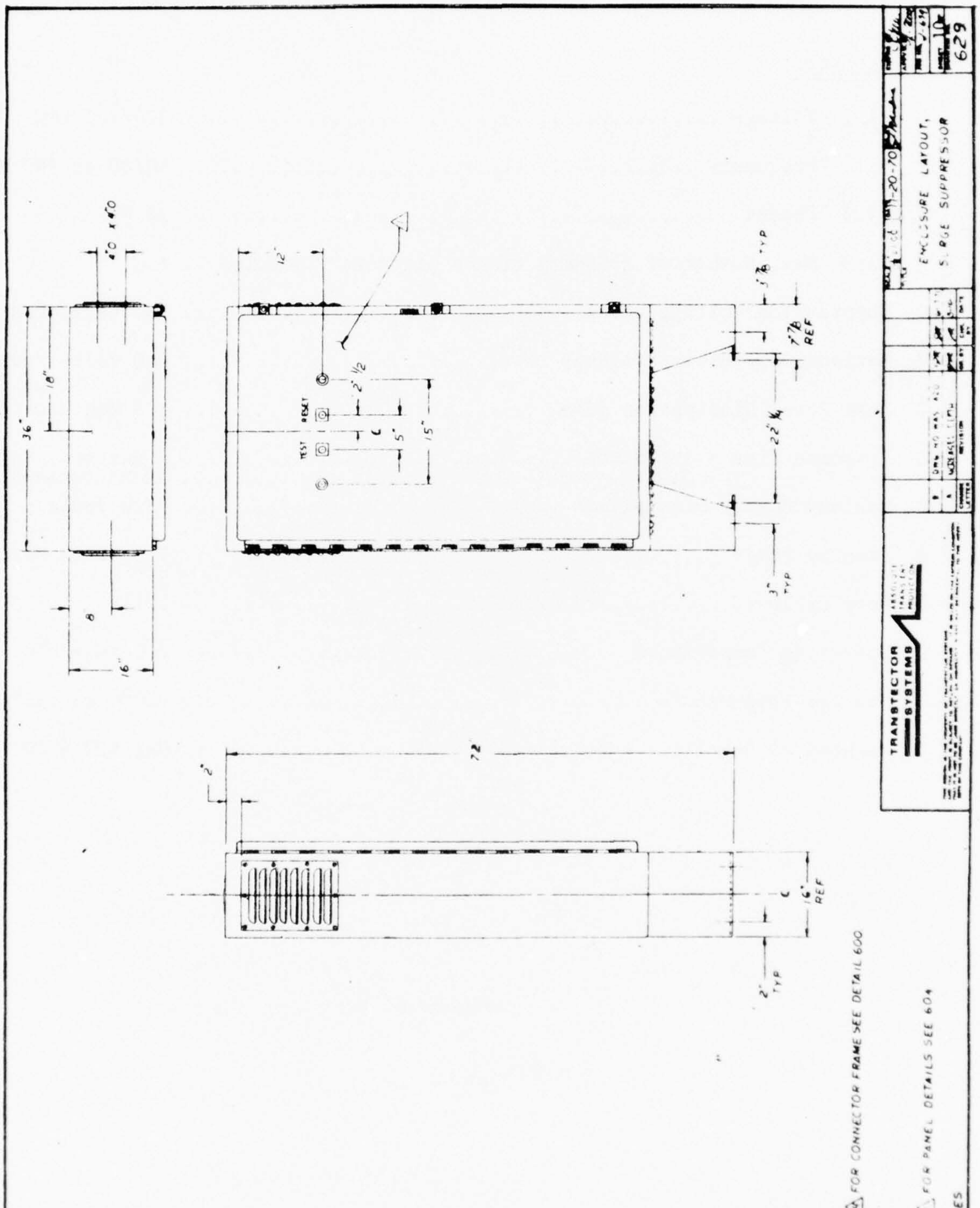

TRANSTECTOR SYSTEMS
ENCLOSURE LAYOUT, SURGE SUPPRESSOR
629
TEST
RESET
FOR CONNECTOR FRAME SEE DETAIL 600
FOR PANEL DETAILS SEE 604
NOTES

Figure 5A

SPECIFICATION: ACP10,000-120W

1.0 GENERAL:

1.1	Voltage	120/208 VAC
1.2	Frequency	50/60 or 400 Hz
1.3	Phases	3Ø Wye
1.4	Max. Number of (150Amp) Branch Circuits Protected	6
2.0	Suppression Voltage Level	200 Volts Peak
3.0	Maximum Suppression Voltage Level	400 Volts Peak
4.0	Peak Power Dissipation (1ms)	1.5 Meg Watt
5.0	Response Time - 1st Stage	5 Nanosec. Max.
	2nd Stage	10 Microsec Max.
6.0	Maximum Energy Dissipation	2500 Joules
7.0	Standby Power	7.5 Watts Max.
8.0	Duty Cycle	.01%
9.0	Operating Temperature	$0^{o}C$ to $+50^{o}C$
10.0	Storage Temperature	$-20^{o}C$ to $+85^{o}C$
11.0	Mechanical Details - Weather Proof	Dwg 629 RECC

Figure 6

counter is mounted in the front door of the enclosure for ease of reading and safety. It counts the number of surges the protector suppresses, if the surges are 500 nanoseconds or greater. This means that the counter does not count all the transients suppressed. (i.e. The ACP10,000 responds in the 5 nanosecond region.) The counter must also detect a minimum of 1000 nanojoules of energy before it will count.

ACP1000 - (Manufactured for 120, 240 or 480 VAC Service)

MECHANICAL

The controls and power electronics are located in a Nema 12 enclosure, 20" x 16" x 6". It weighs approximately 45 lbs. (Figures 7 and 8.)

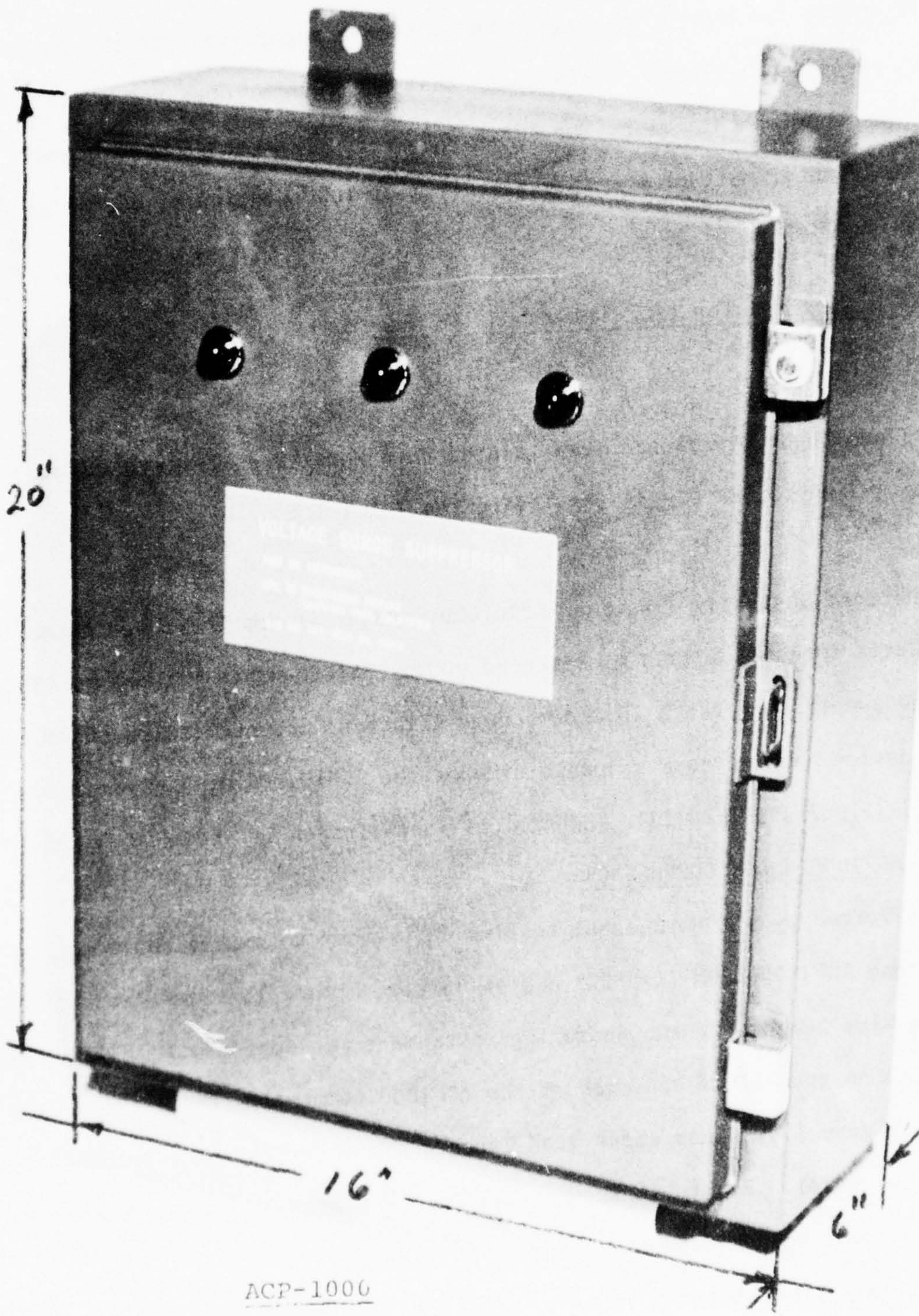
ELECTRICAL

The unit functions basically like the ACP10,000, except it has the power capability of 105,000 watts total (1 X 1000 microsecond pulse) 35,000 watts per phase. This is equivalent to suppressing a 8 X 20 microsecond lightning induced strike of 25,000 amps. This device has the same response time as the ACP10,000 of 5 nanoseconds. See Summary Spec. (Figures 9 thru 13). Electrical installation is shown in Figure 14.

TESTS OF THE ACP1000 SURGE SUPPRESSOR

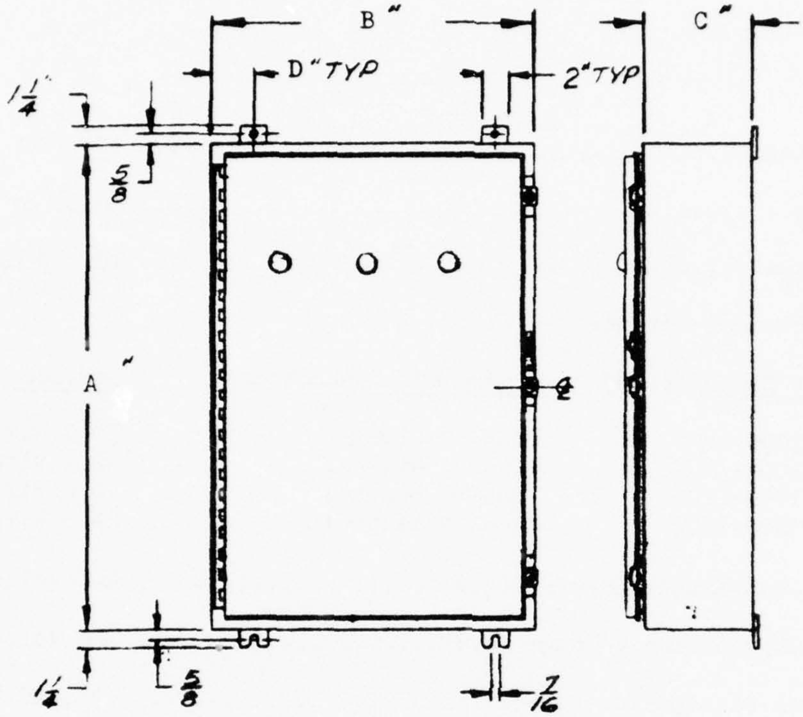
Tests were performed by a governmental testing laboratory to verify the functional parameter of the ACP1000-120W (120/208 3 & 4W unit). Figure 15 shows the test setup. Note that the wire lenghts to the measuring instrument was approximately 42". The results are not as good as if measured at the ACP1000 terminal. Figure 16 is the plot of data (Figure 17). This shows lead lenghts are very important to fast response and low clamping level. Figure 18 shows oscillograph of the 35 joule transient un-suppressed, and then suppressed.

In conclusion, this protector can suppress 35 joules of energy (delivered in 30 micro-sec) with a clamping ratio of 1.5:1.



ACP-1000

Figure 7



ACP1000	A	B	C	D
-120D -120W -120T	20	16	6	3
-120S	16	12	6	$1\frac{1}{4}$

NEMA TYPE 12

Dimensions in inches.

Figure 8

SPECIFICATION: ACP1000-120

1.0 GENERAL:

1.1	Voltage	120 VAC
1.2	Frequency	50/60 or 400 Hz
1.3	Phases	1Ø, 2Ø or 3Ø (See P/N)
1.4	Electrical Service	

Part Number (P/N)	Suppressor Connection	Service
ACP1000-120D	Line to Line	3Ø 3 Wire DELTA
ACP1000-120W	Line to Neutral	3Ø 4 Wire WYE
ACP1000-120S	Line to Neutral	1Ø 2 Wire
ACP1000-120T	Line to Neutral	2Ø 3 Wire

2.0	Suppression Voltage Level	200 Volts Peak
3.0	Maximum Suppression Voltage Level	300 Volts Peak
4.0	Peak Power Dissipation (1ms)	35,000 Watts/Phase 105,000 Watts Total/ for 3 phases
5.0	Response Time	5 Nanosec. Max.
6.0	Standby Power	10 Watts Max./Phase
7.0	Duty Cycle	.01%
8.0	Operating Temperature	$0^{o}C$ to $+50^{o}C$
9.0	Storage Temperature	$-20^{o}C$ to $+85^{o}C$
10.0	Mechanical Details	SK1872 Dwg.
	2Ø, 3Ø, Suppressor	20"H x 16"W x 6"D
	1Ø Suppressor	16"H x 12"W x 6"D
11.0	Electrical Installation	Dwg. 1091

Figure 9

SPECIFICATION: ACP1000-240

1.0 GENERAL:

1.1	Voltage..	240 VAC
1.2	Frequency..	50/60 or 400 Hz
1.3	Phases..	1Ø, or 3Ø (See P/N)
1.4	Electrical Service:	

Part Number (P/N)	Suppressor Connection	Service
ACP1000-240D	Line to Line	3Ø, 3 Wire DELTA
ACP1000-240W	Line to Neutral	3Ø, 4 Wire WYE
ACP1000-240S	Line to Neutral	1Ø, 2 Wire

2.0	Suppression Voltage Level................................	400 Volts Peak
3.0	Maximum Suppression Voltage Level........................	600 Volts Peak
4.0	Peak Power Dissipation (1ms)............................	35,000 Watts/Phase 105,000 Watts Total/ for 3 phases
5.0	Response Time..	5 Nanosec. Max.
6.0	Standby Power..	10 Watts Max./Phase
7.0	Duty Cycle..	.01%
8.0	Operating Temperature................................	0°C to +50°C
9.0	Storage Temperature................................	-20°C to +85°C
10.0	Mechanical Details................................	Dwg. SK1872
	3Ø Suppressor..	20"H x 16"W x 6"D
	1Ø Suppressor..	16"H x 12"W x 6"D
11.0	Electrical Installation................................	Dwg. 1091

Figure 10

SPECIFICATION: ACP1000-480

1.0 GENERAL:

1.1 Voltage.. 480 VAC

1.2 Frequency...................................... 50/60 or 400 Hz

1.3 Phases... 1Ø, or 3Ø (See P/N)

1.4 Electrical Service:

Part Number (P/N)	Suppressor Connection	Service
ACP1000-480D	Line to Line	3Ø 3 Wire DELTA
ACP1000-480W	Line to Neutral	3Ø 4 Wire WYE
ACP1000-480S	Line to Neutral	1Ø 2 Wire

2.0 Suppression Voltage Level............................. 800 Volts Peak

3.0 Maximum Suppression Voltage Level..................... 1000 Volts Peak

4.0 Peak Power Dissipation (1ms).......................... 35,000 Watts/Phase 105,000 Watts Total/ for 3 phases

5.0 Response Time... 5 Nanosec. Max.

6.0 Standby Power... 10 Watts Max./Phase

7.0 Duty Cycle.. .01%

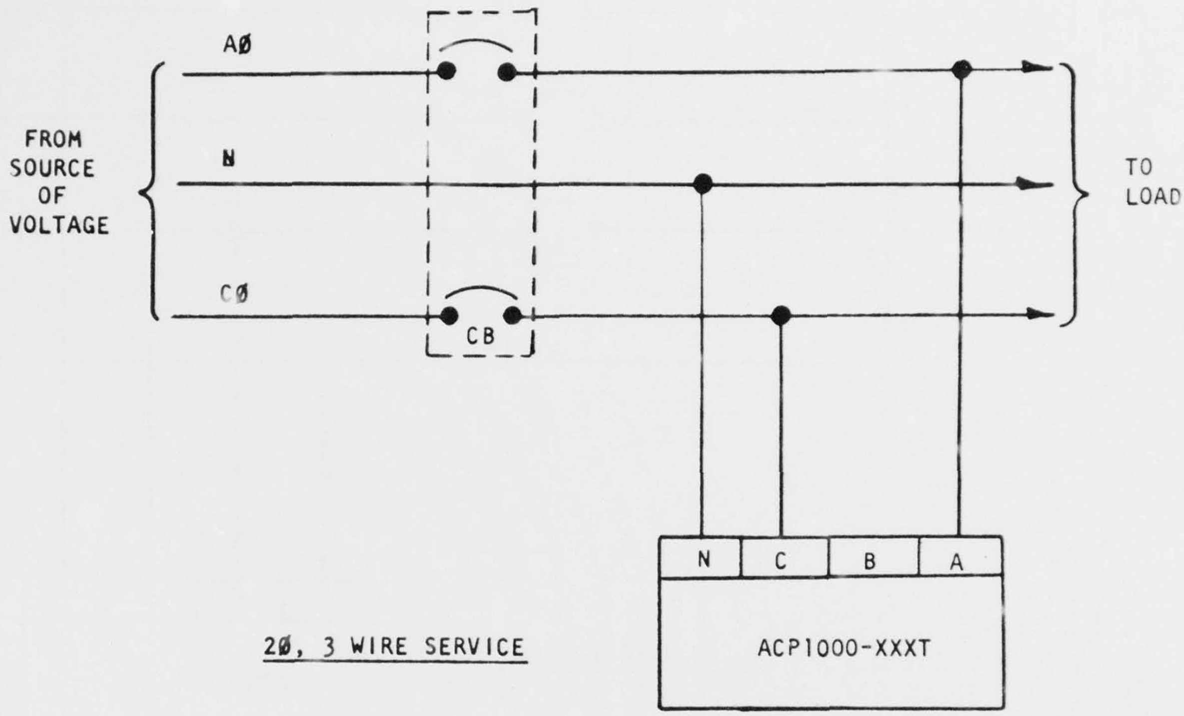
8.0 Operating Temperature................................. 0°C to +50°C

9.0 Storage Temperature................................... -20°C to +85°C

10.0 Mechanical Details.................................... Dwg. SK1872

11.0 Electrical Installation............................... Dwg. 1091

Figure 11


AØ
FROM
SOURCE
OF
VOLTAGE
N
CØ
CB
TO
LOAD
N
C
B
A
2Ø, 3 WIRE SERVICE
ACP1000-XXXT

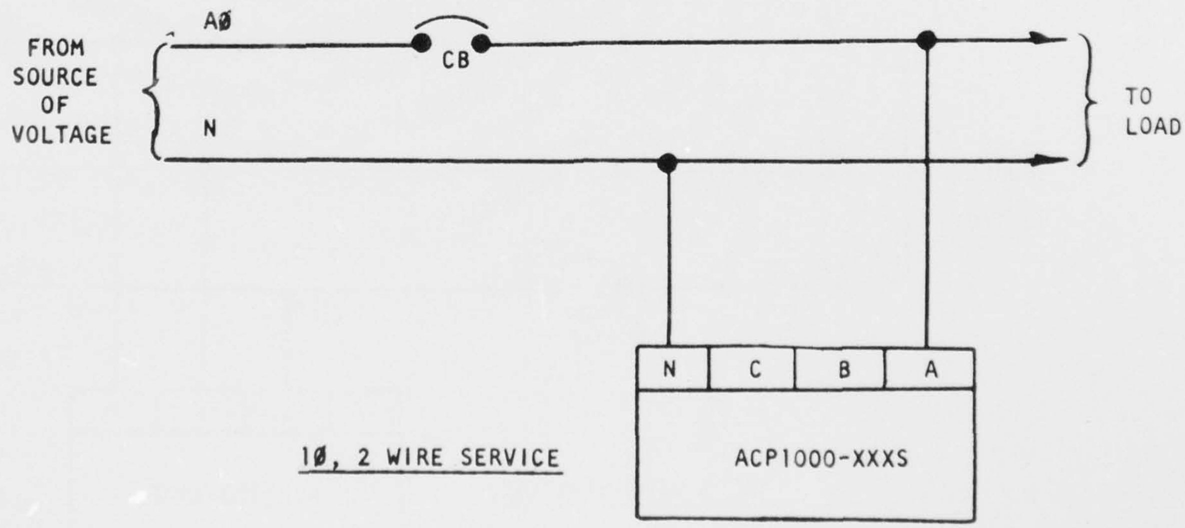
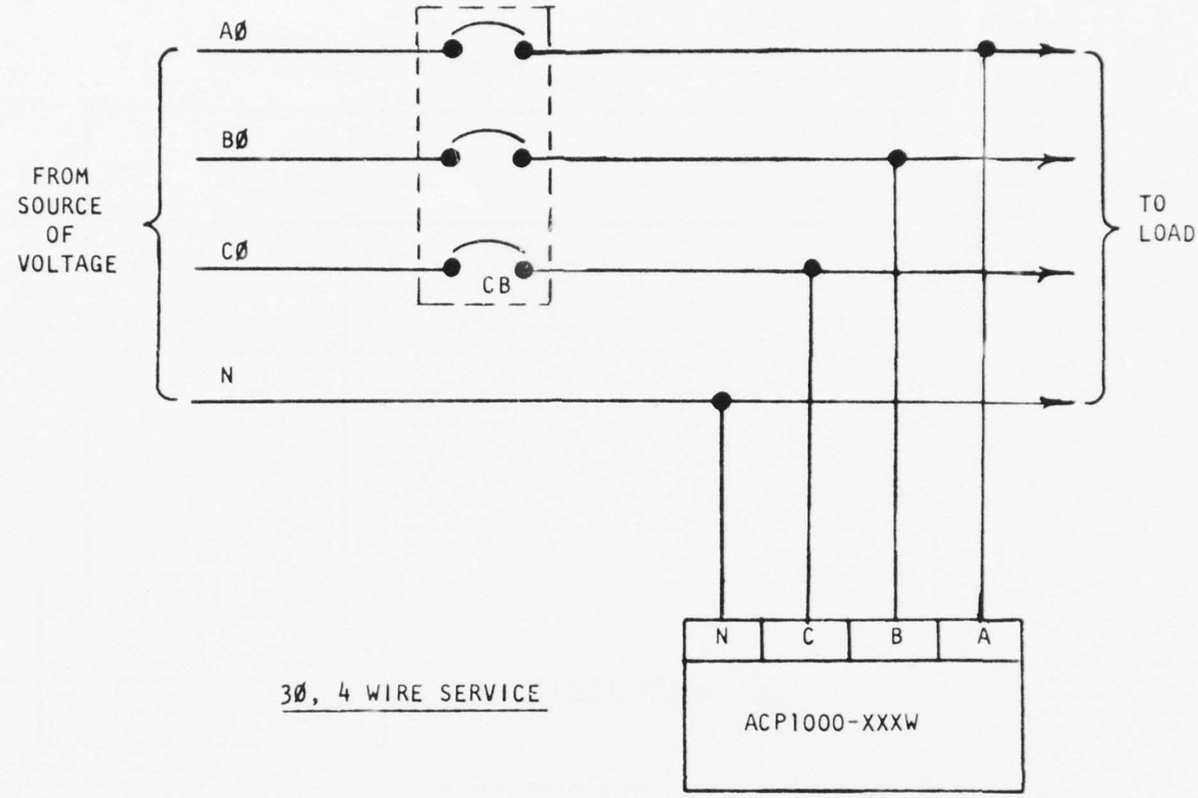
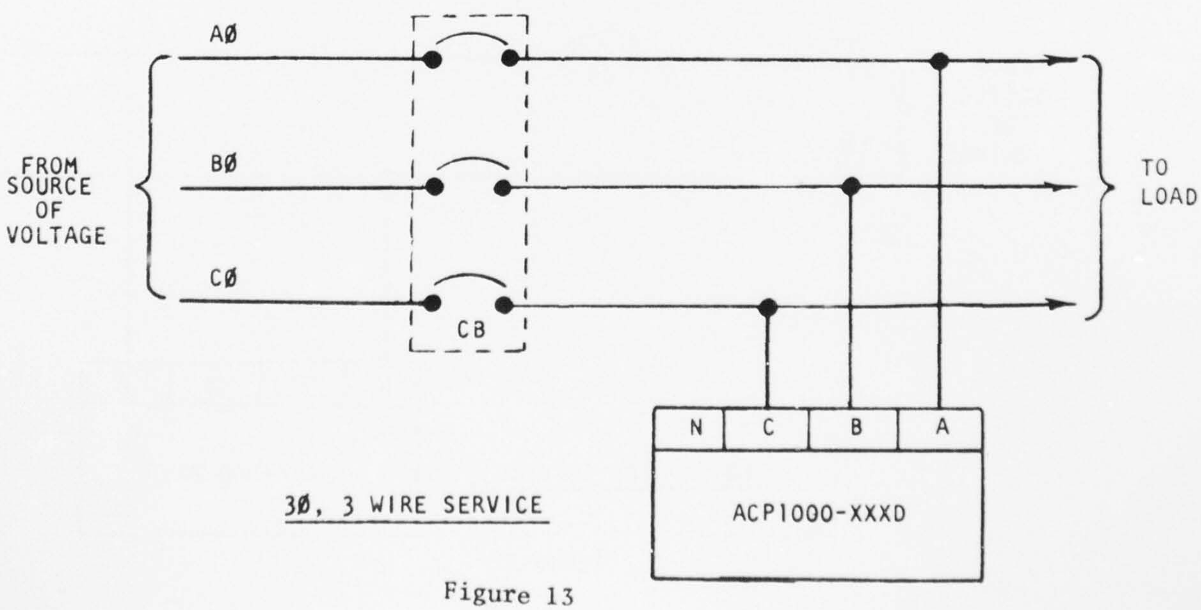

FROM
SOURCE
OF
VOLTAGE
AØ
CB
N
TO
LOAD
N
C
B
A
1Ø, 2 WIRE SERVICE
ACP1000-XXXS

Figure 12



3Ø, 4 WIRE SERVICE



3Ø, 3 WIRE SERVICE

Figure 13

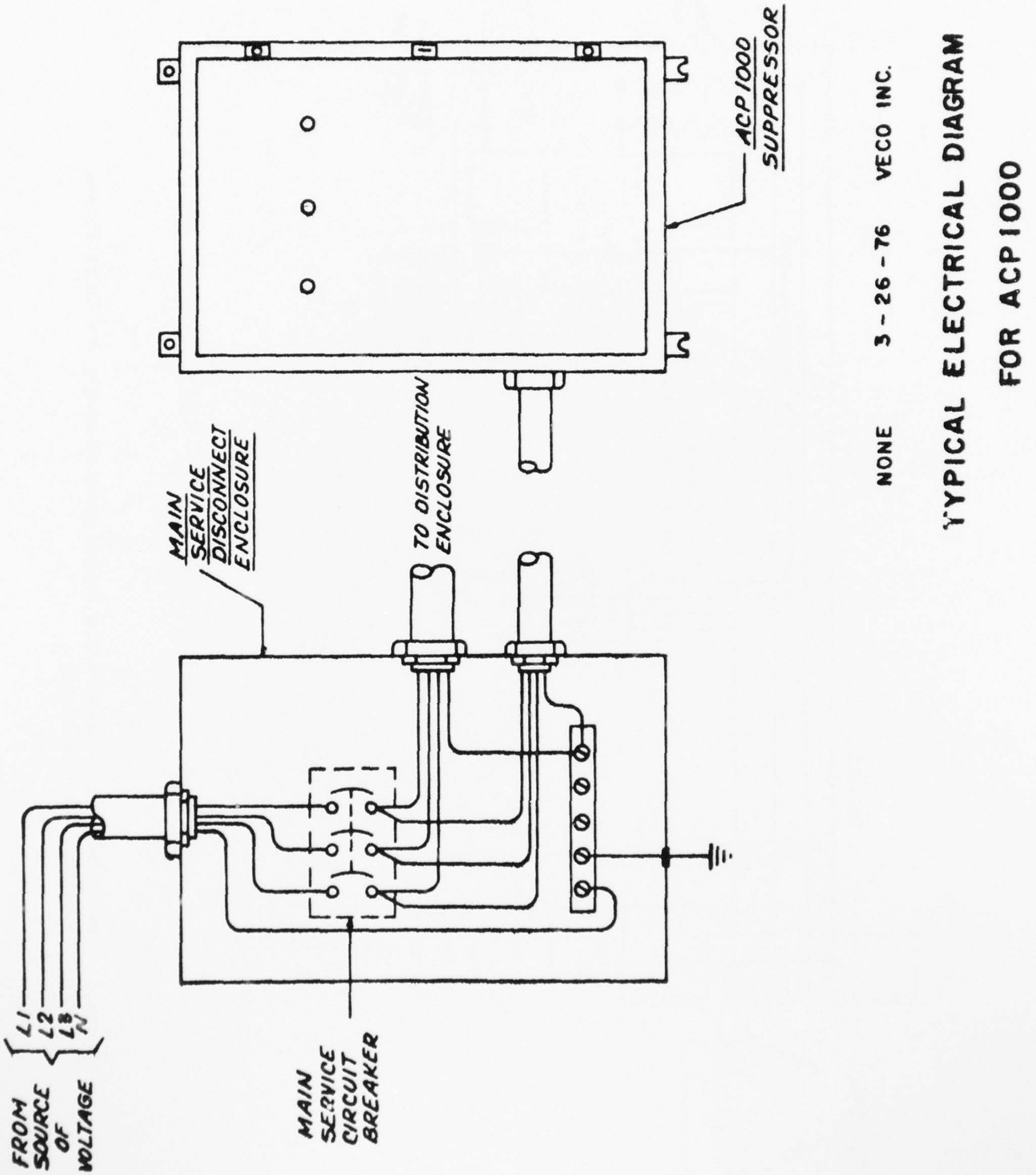

FROM SOURCE OF VOLTAGE
L1
L2
L3
N
MAIN SERVICE CIRCUIT BREAKER
MAIN SERVICE DISCONNECT ENCLOSURE
TO DISTRIBUTION ENCLOSURE
ACP1000 SUPPRESSOR
NONE 3-26-76 VECO INC.
TYPICAL ELECTRICAL DIAGRAM
FOR ACP1000

Figure 14

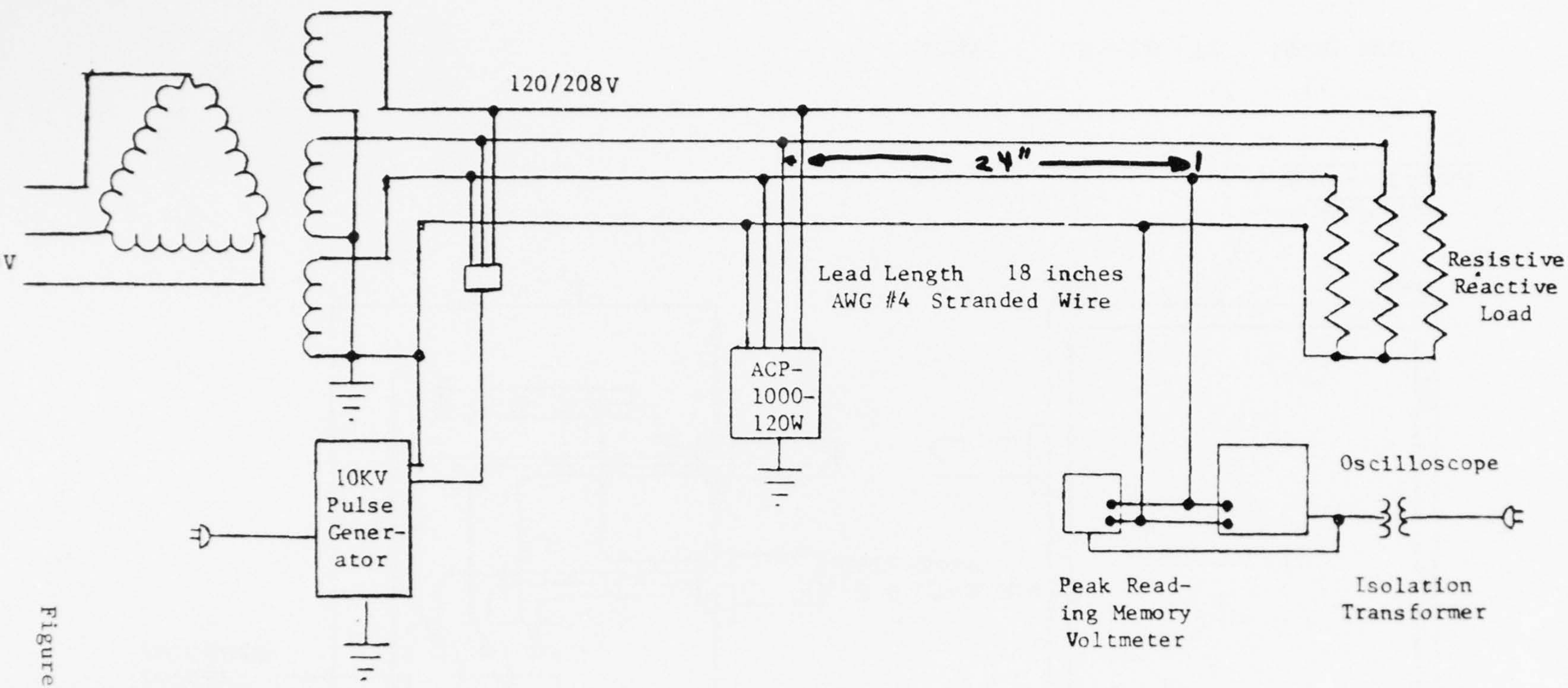


Figure 2. Test Set-Up With Three Phases Pulsed Simultaneously and Three Phases Suppressed Simultaneously.

Figure 15

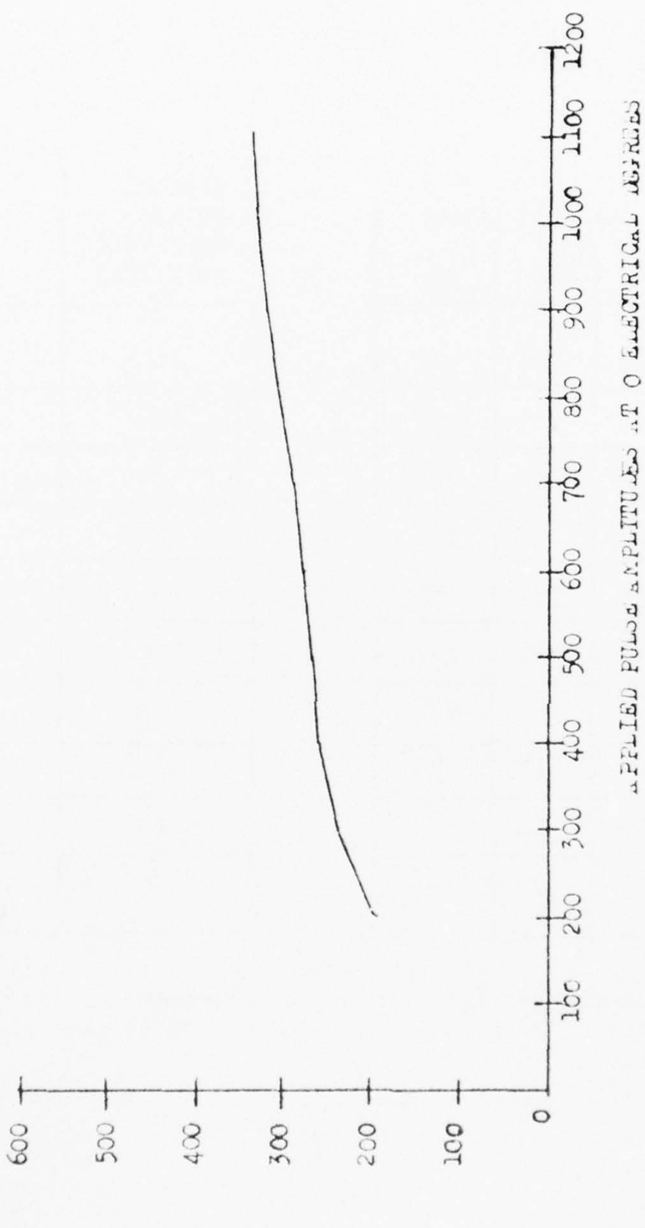


Figure 4. Voltage clamping levels for section A of Transtector ACP-1000-120W for 30 microsecond duration impulse voltage transients. 35 JOULES

Figure 16

Clamping Voltage Levels of Transtector Systems, Model Apc-1000-120W Suppressor Pulses of 30 Microseconds Duration Applied at 0 and 90 Electrical Degrees.

0 Degrees

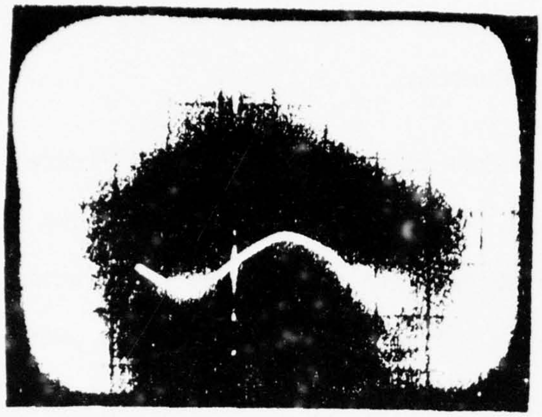
APPLIED PULSE PEAK VOLT AMPLITUDE	CLAMPING LEVEL		
	ØA	ØB	ØC
200	200	200	200
300	240	225	220
400	260	240	245
500	270	260	260
600	280	270	265
700	290	285	280
800	310	300	290
900	325	315	305
1000	335	325	325
1100	340	335	340

90 Degrees

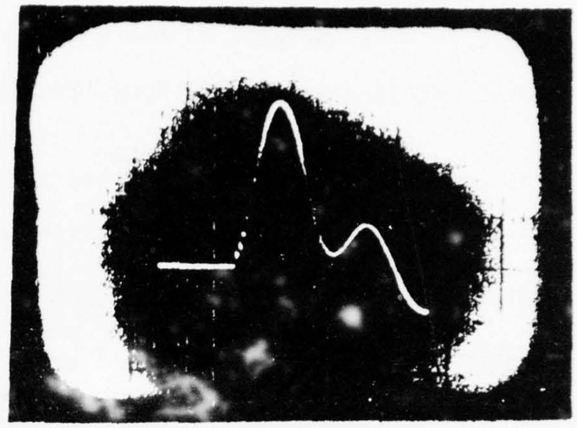
APPLIED PULSE PEAK VOLT AMPLITUDE	CLAMPING LEVEL		
	ØA	ØB	ØC
200	200	200	200
300	225	210	220
400	240	220	225
500	245	225	230
600	260	240	245
700	265	250	260
800	270	265	270
900	285	280	290
1000	300	285	305
1100	315	305	320

Note: The maximum energy stored in pulse generator for 1100 volt pulse for 30 microseconds duration is 35 joules. Pulse rise time approximately 15 microseconds.

FIGURE 17

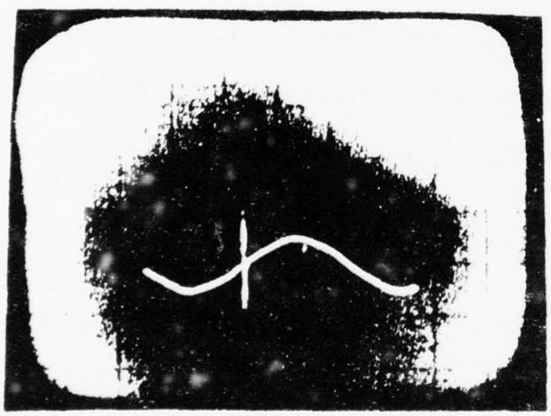


340V/cm

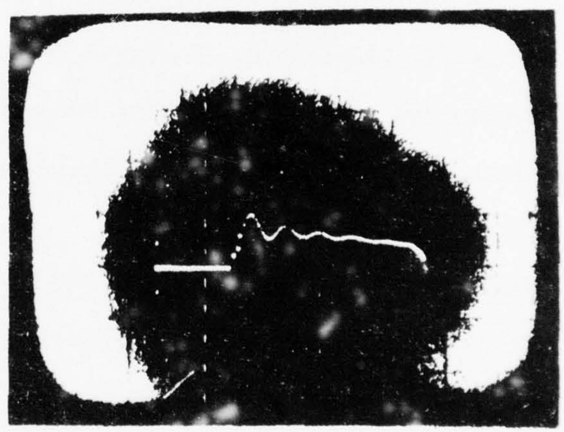


Approximate 1100 Peak Volt
Unsuppressed Pulse

Unsuppressed Pulse With Oscilloscope
Sweepseppd 20 Microseconds/cm



340V/cm



Pulse Suppressed to 355 Peak
Volts Using Transtector Model
ACP-1000-120 Suppressor

Suppressed Pulse With Oscilloscope
Sweepspeed 20 Microseconds/cm

Figure 6. Suppression of a 1100 Peak Volt 30 Microsecond Duration (35 Joule) Pulse Using Transtector Systems ACP-1000-120W Suppressor.

Figure 18

FAA/ARTCC - Longmont, Colorado

Early in 1971, several of the slower responding (10 microsec) models of the ACP10,000 were installed in FAA Air Route Traffic Control Centers.

The Longmont, Colorado, ARTCC had the ACP10,000-120W installed as shown in Figure 18A. It protected the seven critical 150 amp, 120/208 3 phase 4 wire circuits. These circuits feeding the IBM 360's, had numerous problems with outages due to induced lightning, and switching surges on the power line. It also protected the computers from a more common problem of fuse arching. An FAA study showed that if a 150 amp fuse blew, the transient generated was a pulse of 2000 amps for 2 millisec. It would travel down other branch service legs and damage equipment.

After installation of the ACP10,000 the records showed no outages due to overvoltage surges or transients. During a 3-1/2 year period, a total number of transients suppressed were 597,332. The counter used, had a maximum response time of 5 millisec. Because of the slow counting time, many of the high speed transients were suppressed but not detected.

EAST COAST SATELLITE TRACKING STATION

In December of 1974, Transtector Systems received an urgent message from a well-known National Corporation. In an insuing meeting, the management of Transtector was advised that this major corporation managed a satellite tracking station for an U.S. Government Agency, and that for some time, had been having serious problems with most of their electronic equipment and instrumentation at the tracking station. The problems were due to induced lightning strikes and high energy switching transients, on the A.C. power line feeding the site. They had on many occassions, suffered great economic losses, and even worse, could have lost (so to speak) "satellites down range". After evaluation of other methods of protection, they asked if there was anything Transtector could do to solve the problem. Technical review and analysis of the information

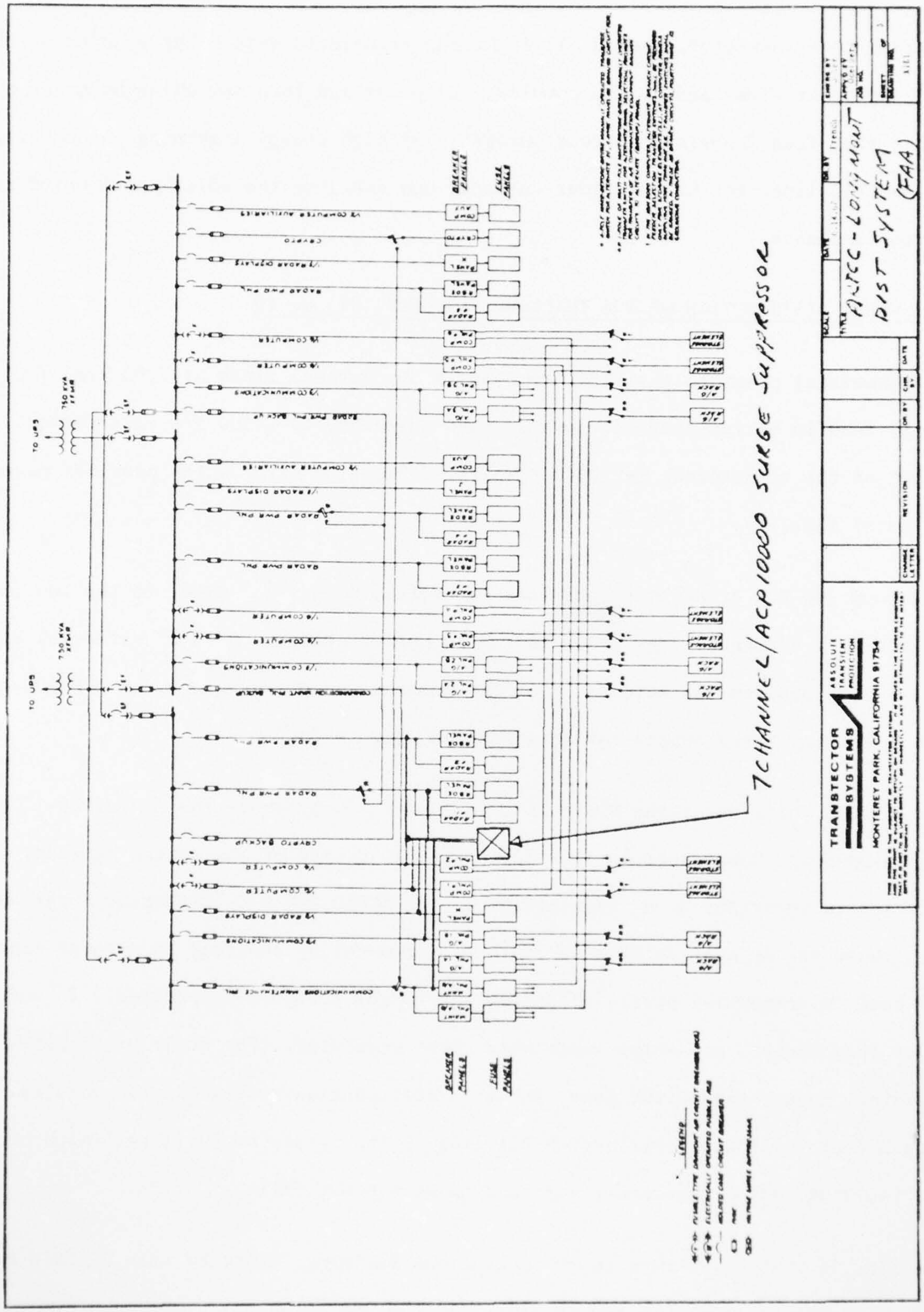

7CHANNEL/ACP10000 SURGE SUPPRESSOR
TRANSTECTOR SYSTEMS
ABSOLUTE TRANSIENT PROTECTION
MONTEREY PARK, CALIFORNIA 91754
DIST SYSTEM
(FAA)

Figure 18A

provided to Transtector, showed 1) lightning transients were being induced on the 7200 VAC power line feeding the complex, 2) power and load switching by other users on the same feed, causing numerous outages, 3) high energy lightning was entering the 480 VAC lines to the 48' radar antennas and damaging the solid-state motor drives for the antennas.

A.C. POWER DISTRIBUTION OF THE TRACKING FACILITY, Figure 19

The commercial power to the facility comes from overhead lines at 7200 Vrms (Delta) and is feed in buried conduit, several hundred yards, to a 500 KVA transformer. The output of the transformer is 120/208 volts, 3 Phase, 4 Wire, which provides power to the total facility.

A step-up 100 KVA transformer provides 480 Volts, 3 Phase, 3 Wire, to the two (2) 48' tracking antennas. The power is run in buried conduit (6" x 6" wireways) approximately 600 yards to the antennas. At the antenna end of each feed, an ACP1000-480D, A.C. Lightning Surge Suppressor is installed, Figure 20.

The 120/208 Volts enter the Power Distribution Building where the ACP10,000-120W Lightning Surge Suppressor is located, on the load side of the switching gear. This location is important as during testing of the ACP10,000 A.C. Lightning Surge Suppressor, there was as many as 60 transients produced during transfer to a motor generator, and back to commercial power, which the suppressor promptly suppressed. In addition, short lead lenghts and large cable size wires were used. The Power Distribution Building, houses the switch gear, and main distribution system for the complex. Attached to the Power Distribution Building is the Generator Building, which houses the two 250KV motor generators for back-up when power fails.

The 120/208 Volt power runs to the Operations Building, approximately 50 feet away, and other locations within the complex. In the Operation Building, main power

distribution panels are provided for all systems including the UPS (Uninterrupted Power System) which feeds the computer, control systems, and communication equipment.

Solved the Problem

Transtector Systems recommended that the total site be protected by Transtector's Model ACP10,000-120W, Figure 4 (1.5 million watt transient suppressor) placed at its (1600 amp) main power feed and an ACP1000-480D, Figure 7 (105,000 watt transient suppressor) placed at each 48' antenna, to protect the antenna's SCR solid-state motor drives and controls. In May of 1975, the products were delivered and installed under the supervision of Transtector Systems installation engineers.

After more than 18 months (1-1/2 years) of continuous service, and continuous monitoring by the personnel of the customer, the problem was completely solved.

There had been no shutdowns of the computer, control, radar, communication systems, radio transmitters, or any other solid-state devices within the complex, resulting from A.C. power line transients or surges, even though the complex was subjected to a total of 174,402 damaging transients as recorded by the high speed digital transient counter which is built into the system. As one can see from Figure 21, during certain peak periods, over nine thousand (9,000) transients were recorded in a 24 hour period. Any one of the transients was considered to be of a damaging nature. (Reference Figure 21). It is important to note that any day on which the ACP10,000 suppressed even one time, lost information, shut-down or destruction could have occurred - if the unit was not there.

A 550 day period of which transients were counted on 511 days, shows the system required protection by the suppressor on over 93 percent of the days. The minimum on any day was 1 suppression, and the maximum was 9,028 suppressions on June 26, 1975. On three other occassions the count exceeded 9,000 suppressions in a 24 hour period. The average suppressions per day required for the 18 month period was 10.8.

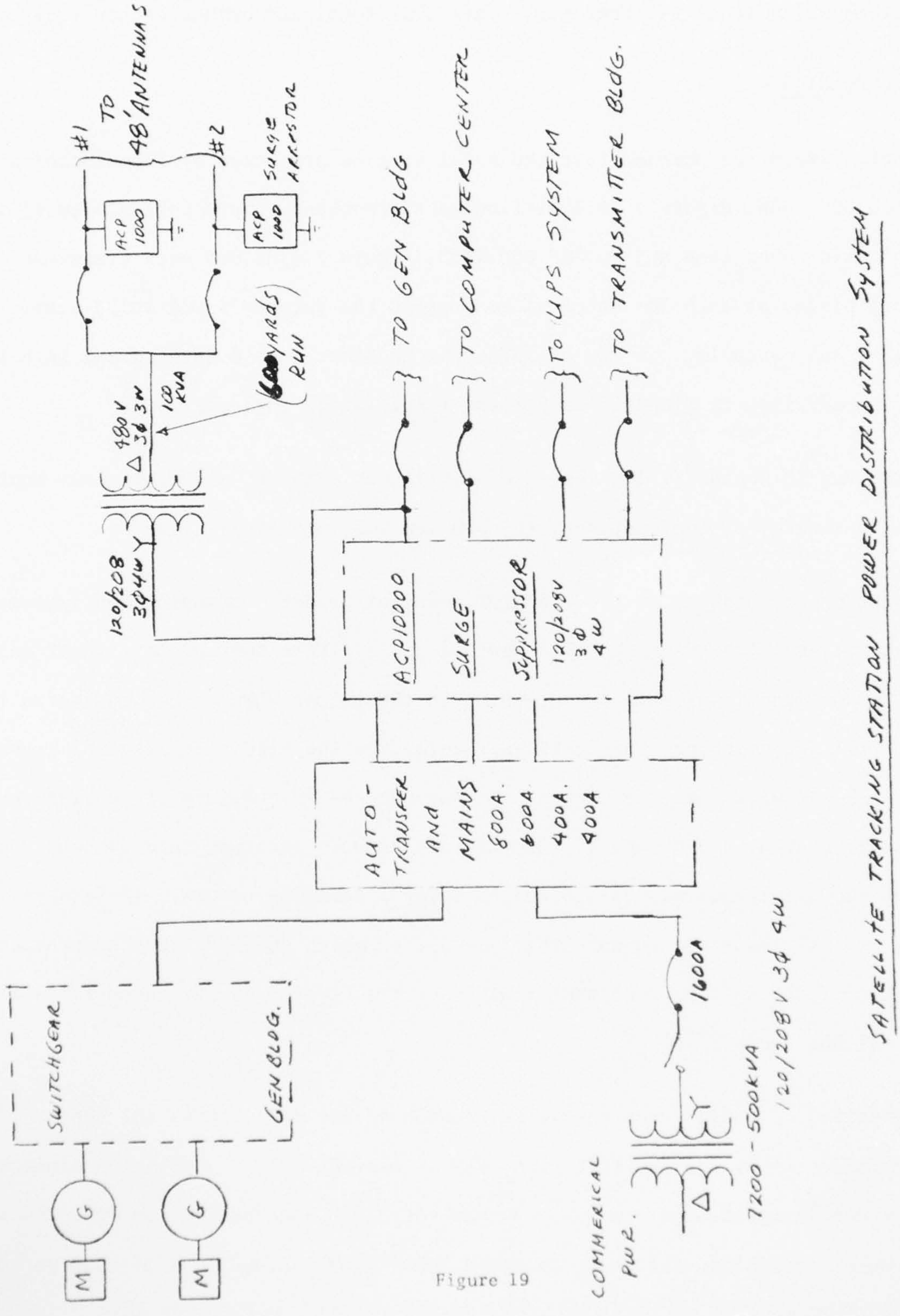
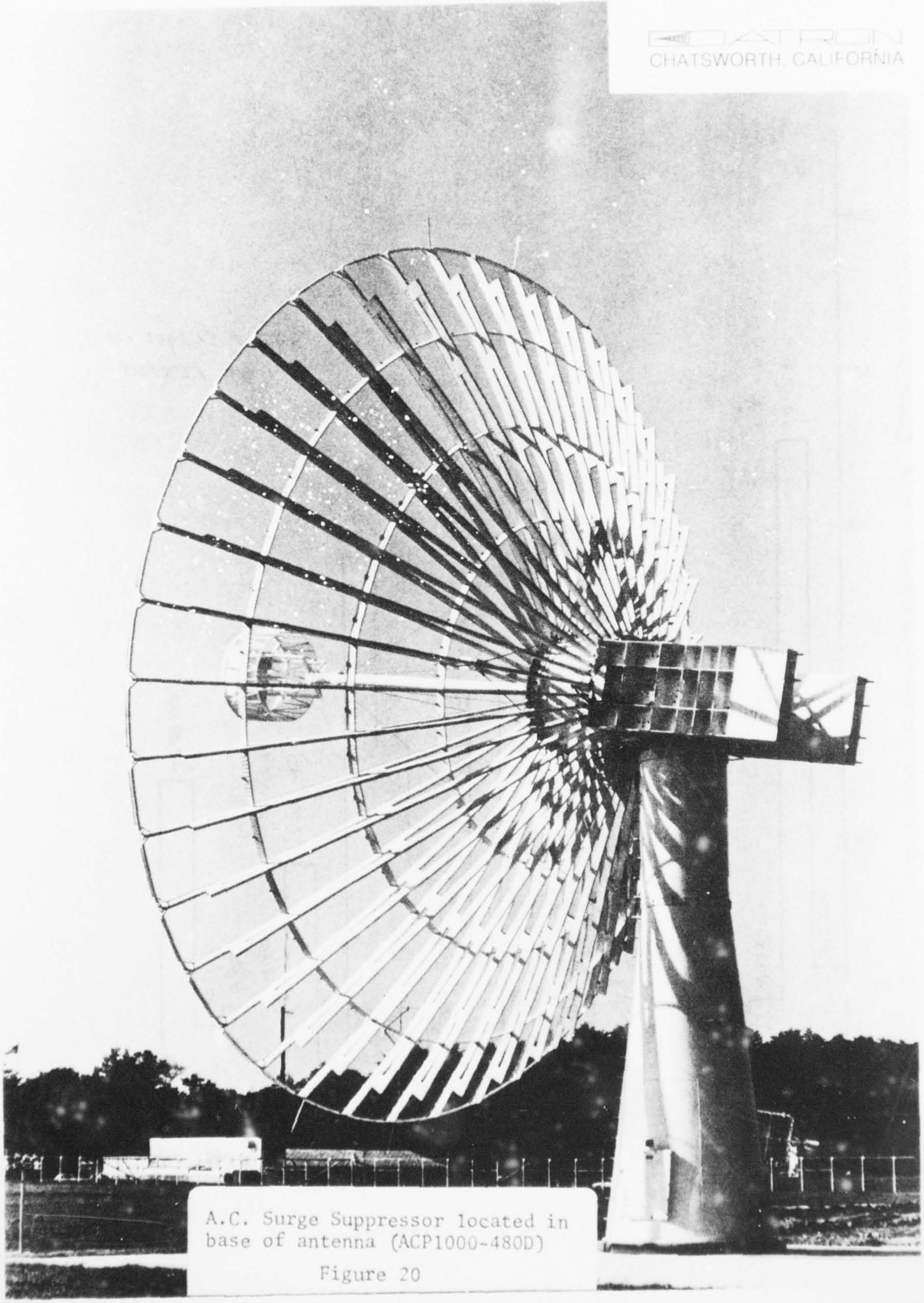
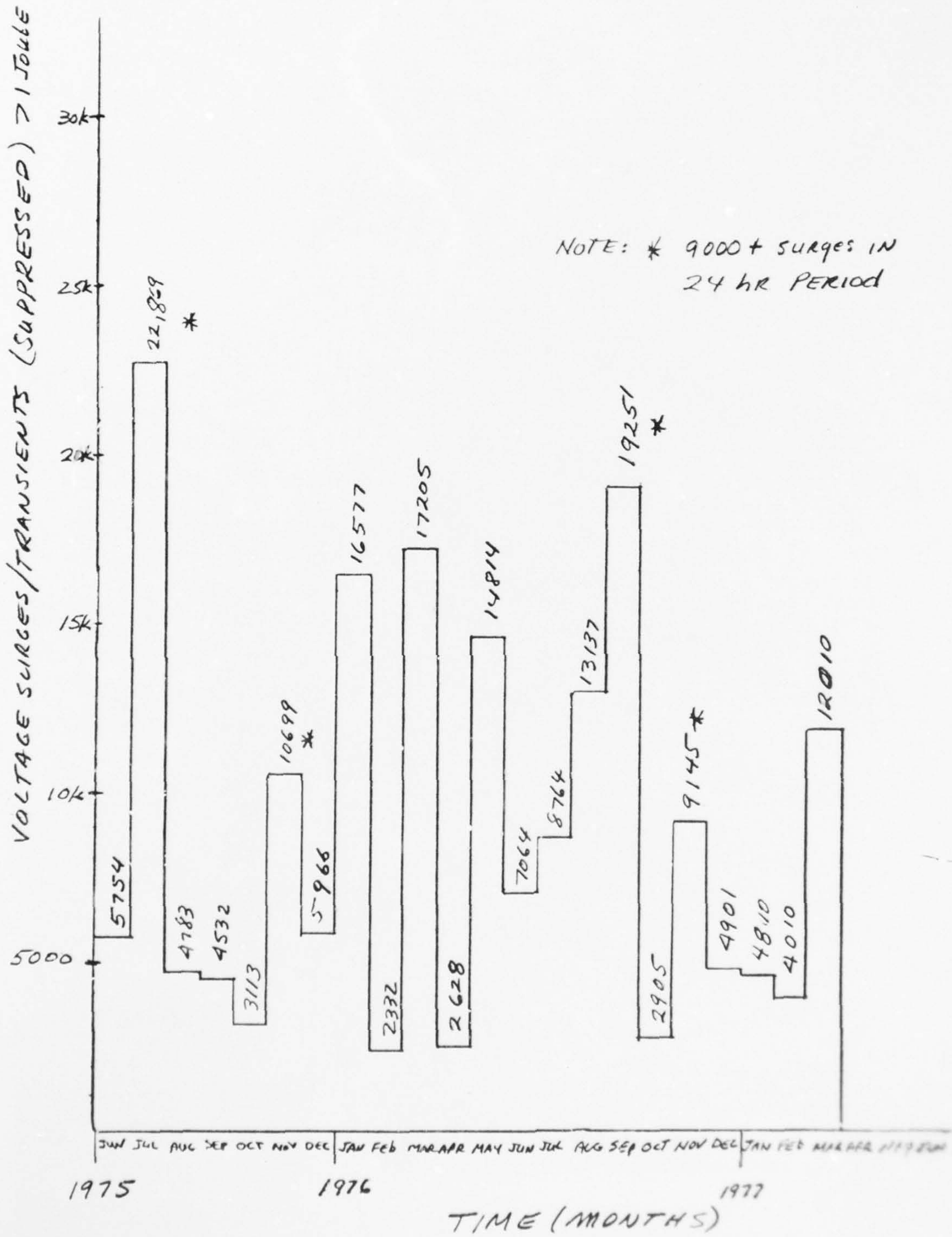

SATELLITE TRACKING STATION POWER DISTRIBUTION SYSTEM
TO 48' ANTENNAS
#1
#2
ACP 1000
ACP 1000
SURGE ARRESTOR
480 V
Δ 3φ 3W
100 KVA
YARDS RUN
120/208
3φ 4W
TO GEN BLDG
TO COMPUTER CENTER
TO UPS SYSTEM
TO TRANSMITTER BLDG.
ACP10000
SURGE
SUPPRESSOR
120/208V
3φ
4W
AUTO-
TRANSFER
AND
MAINS
800A.
800A.
400A.
400A
SWITCHGEAR
GEN BLDG.
G
G
M
M
1600A
COMMERICAL
PWR.
7200 - 500KVA
120/208V 3φ 4W

Figure 19



A.C. Surge Suppressor located in base of antenna (ACP1000-480D)

Figure 20



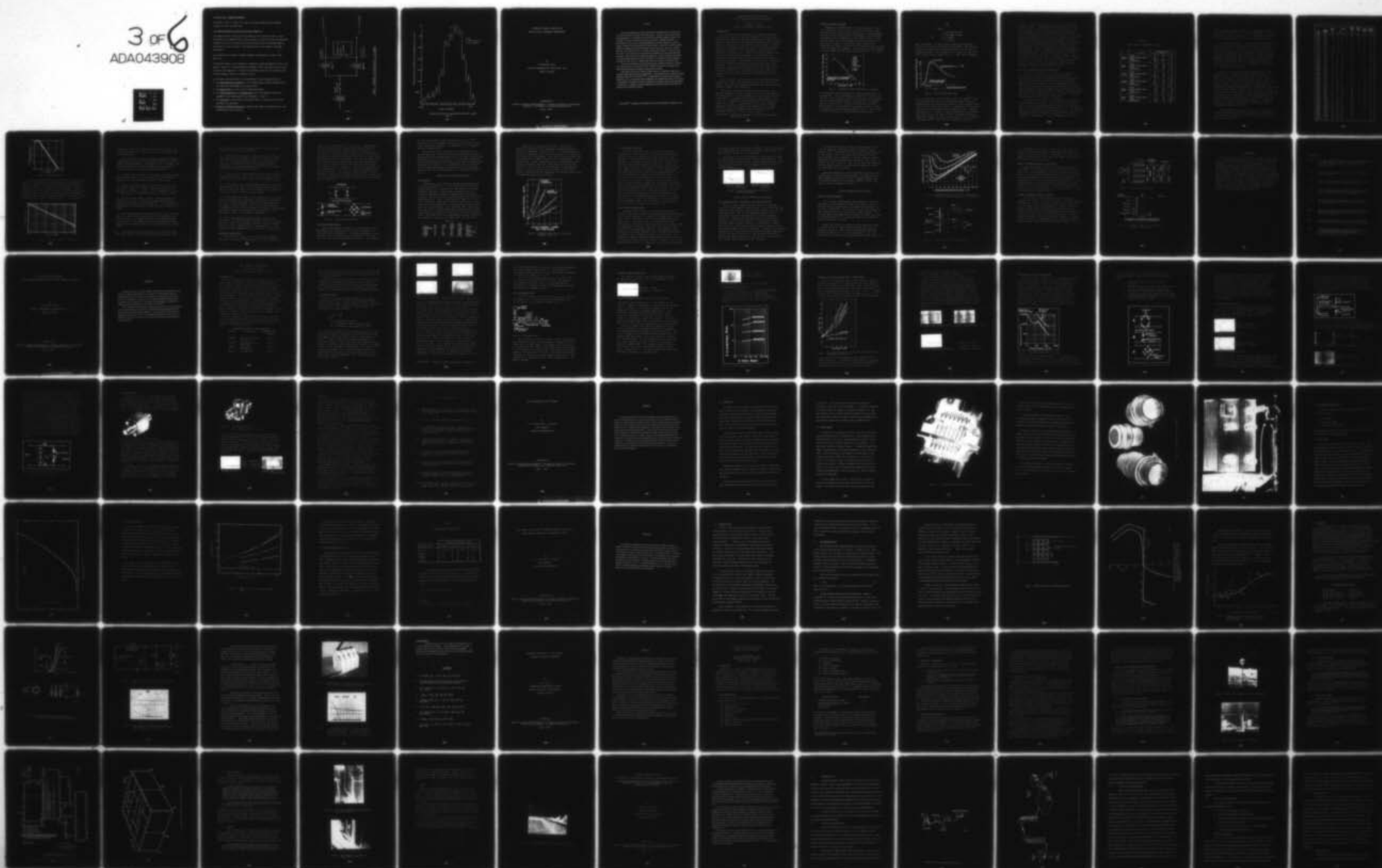
TRANSIENT/SURGES SUPPRESSED - BLPT. TRACKING STATION

Figure 21

AD-A043 908 FEDERAL AVIATION ADMINISTRATION WASHINGTON D C SYSTE--ETC F/G 13/12
FEDERAL AVIATION ADMINISTRATION - FLORIDA INSTITUTE OF TECHNOLO--ETC(U)
MAY 77

UNCLASSIFIED FAA-RD-77-84 NL

3 OF 6
ADA043908



3 OF 6

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AIR FORCE SITE - COMPUTER OPERATIONS

In February, 1976, A.C. power line surges and induced lightning caused numerous outages and loss of critical data.

A.C. Power Distribution of the Air Force Site (Figure 22)

The commercial power is feed into the building to two (2) 480 VAC 3 Phase, 3 Wire Transformers to a 120/208 3 Phase, 4 Wire Secondary. At this point the ACP10,000-120W (Figures 4 and 5) was installed protecting the output of both transformers with its power diode "or" logic circuits. The power then went to the computer center for distribution.

The results were no outages or damaged equipment from lightning or surges on the power line.

The Transient Counter in the suppressor, displayed an interesting profile of the site's problem. Figure 23. During the month of September, 1976, a the total count of 53,020 transients were suppressed. A correlation of weather conditions and discussion with the power company, showed this condition existed.

In conclusion, the major factors to be considered for facility protection are:

1) The Power Suppression Capability is to be large enough to handle the application with concern on what happens if the device fails.
2) The Response Time is to be in the low nanosecond region.
3) The Voltage Suppression and Clamping Ratio must be low enough to protect the equipment at the required power level (Reference 1 above).
4) The Reliability is most important when human life is at stake, and for low cost maintenance and operation.
5) Automatic or Resetable Operation is important for human life applications as well as maintenance and cost factors.

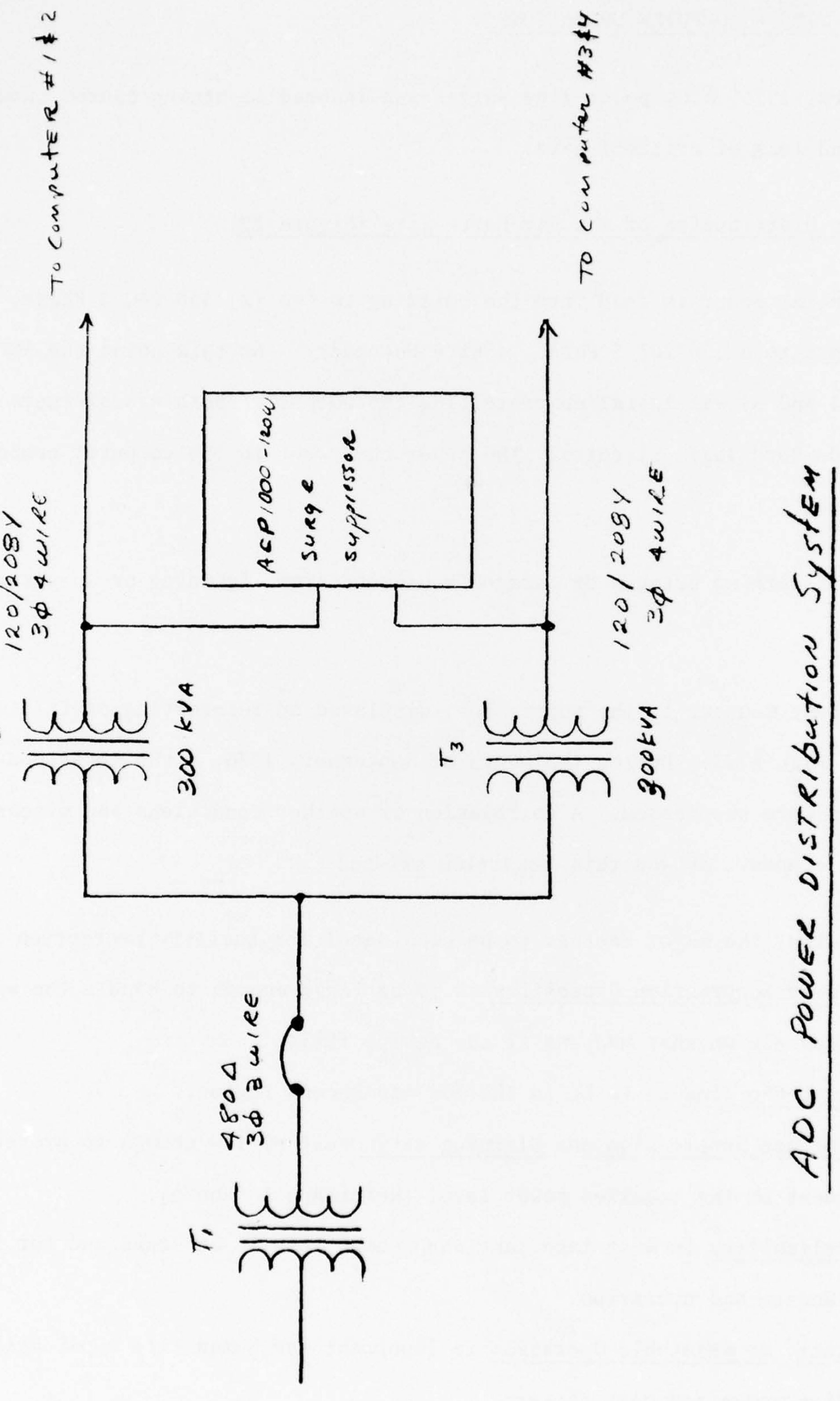
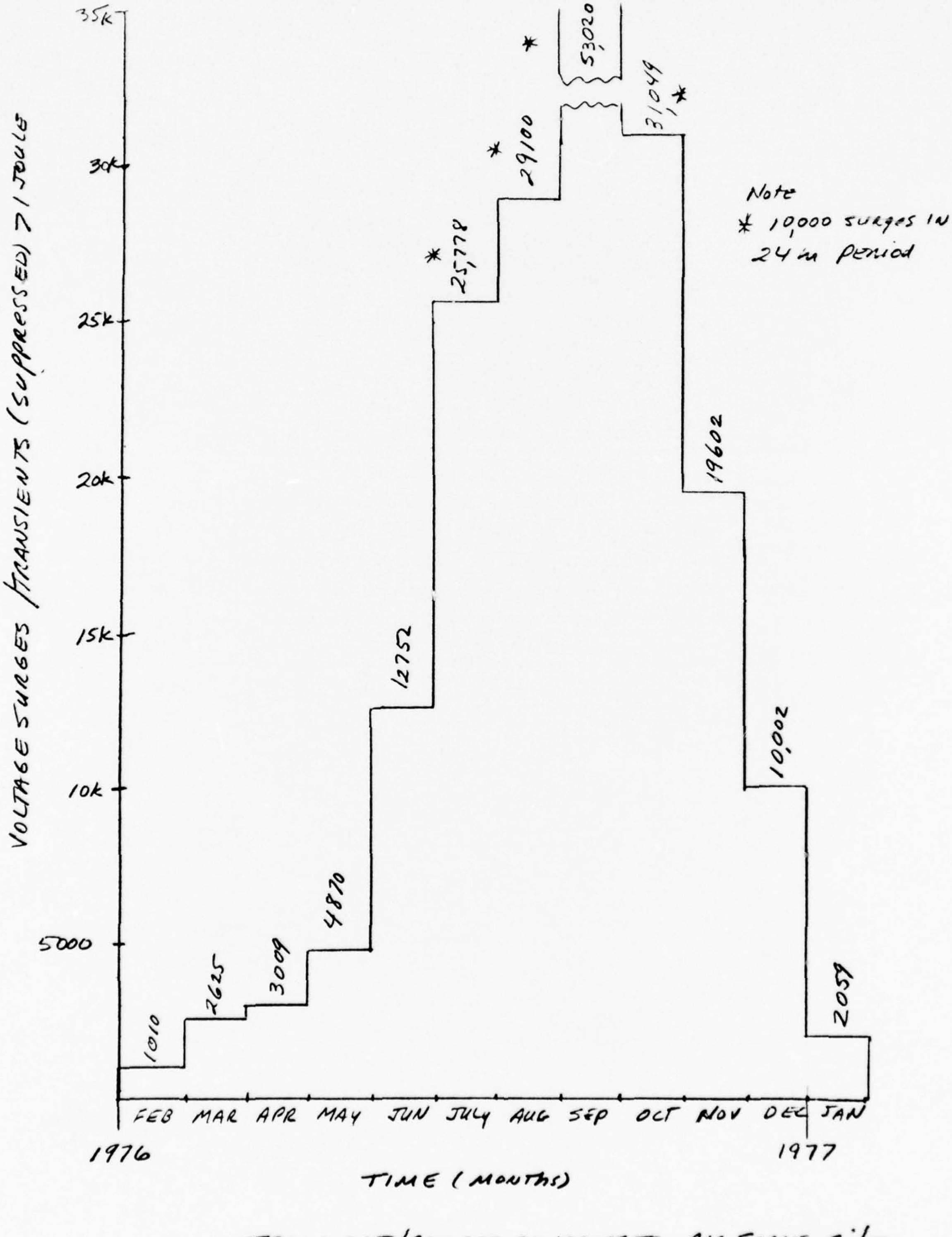

TO COMPUTER #1 & 2
TO COMPUTER #3 & 4
ACP1000-120W
SURGE
SUPPRESSOR
120/208Y
3Φ 4WIRE
120/208Y
3Φ 4WIRE
T2
300 KVA
T3
300KVA
480Δ
3Φ 3WIRE
T1
ADC POWER DISTRIBUTION SYSTEM

Figure 22



TRANSIENT/SURGES SUPPRESSED - AIR FORCE SITE

Figure 23

TRANSIENT VOLTAGE SUPPRESSION USING SILICON AVALANCHE SUPPRESSORS

by

O. Melville Clark

General Semiconductor Industries, Inc.

Tempe, Arizona

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

The early design vacuum tube type electronic equipment was relatively hard to transient voltages by virtue of its construction. However, with the introduction of semiconductors, especially MOS and small area geometry bipolar devices, vulnerability to transient voltages has increased greatly. Voltage transients are generated by many sources, including lightning, switching transients, static discharge, and power line disturbances of various types. Some of the earlier methods used for providing protection included the carbon spark gap, resistors, selinium devices, zener diodes and more recently, metal oxide varistors. Within the past few years, a new device has been developed specifically for protecting solid state circuitry. This is the silicon avalanche suppressor. These particular components are characterized by their small size and ability to dissipate relatively high power transients (1,500 watts for 1 millisecond and 12,000 watts for 2 microseconds).

Two of the main characteristics of the silicon avalanche suppressors include fast response time, of the order of 10^{-12} seconds, and very low clamping factor which provide significant margin of suppression protection.

This report discusses transient voltage sources, and optimum suppression methods using silicon avalanche suppressors. Also discussed are various parameters of devices such as the TransZorb*^{tm}, as manufactured by General Semiconductor Industries, Inc., summarizing both capabilities and limitations of these device types. A comparison of the silicon avalanche suppressor with other suppression components is also made. In addition, specific applications utilizing the silicon avalanche suppressors are described in detail.

* TransZorb^{tm} - Registered Trademark of General Semiconductor Industries, Inc.

TRANSIENT VOLTAGE SUPPRESSION USING SILICON AVALANCHE SUPPRESSORS

O. Melville Clark
General Semiconductor Industries, Inc.

INTRODUCTION

The early design vacuum tube type electronic equipment was relatively hard to transient voltages by virtue of its construction. However, with the introduction of semiconductors, especially MOS and small area geometry bipolar devices, vulnerability to transient voltages has increased greatly. Voltage transients are generated by many sources, including lightning, switching transients, static discharge, and power line disturbances of various types. Some of the earlier methods used for providing protection included the carbon spark gap, resistors, selinium devices, zener diodes and more recently, metal oxide varistors. Within the past few years, a new device has been developed specifically for protecting solid state circuitry. This is the silicon avalanche suppressor. These particular components are characterized by their small size and ability to dissipate relatively high power transients (1,500 watts for 1 millisecond and 12,000 watts for 2 microseconds).

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*TransZorbtm - Registered Trademark of General Semiconductor Industries, Inc.

TRANSIENT VOLTAGE SOURCES

Lightning is probably one of the most awesome natural forces which we accept as part of every day living. The average current in the first return stroke is 20 kiloamperes, with 10% of such strokes being 65 kiloamps or more and with a maximum of 200 kiloamperes for the temprate zones. Peak currents range up to 400 kiloamperes for return strokes in the tropical regions. Electrical fields generated by lightning are coupled into electrical wiring and have resulted in severe damage to equipment. The magnitude of this problem is better understood upon perusing the chart Fig. 1, in which

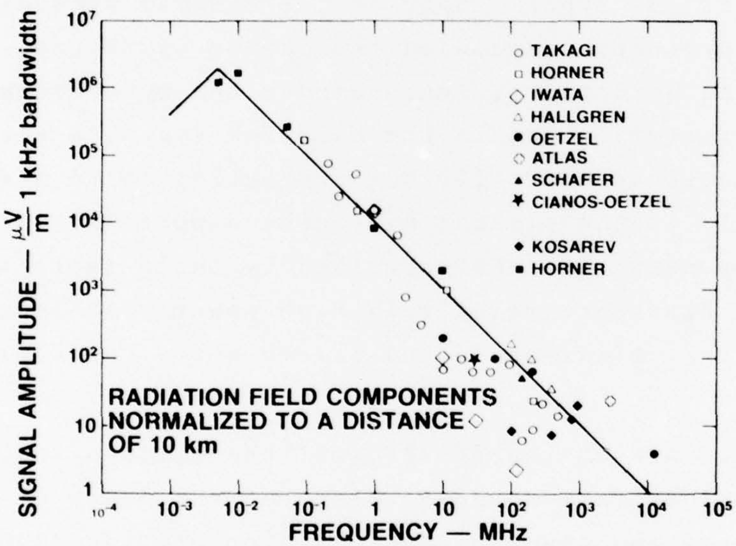

Fig. 1: Lightning Signal Amplitude vs Frequency

is plotted the signal amplitude of radiated lightning versus frequency[1]. This data shown is normalized to strokes at a distance of 10 kilometers; however, using the inverse square law, it can be observed that at a distance of 1 kilometer, electric fields can be in excess of 100 volts per meter. When current is interrupted in an inductive load, a voltage is generated by the collapsing magnetic field. This voltage is given by Farriday's Law of Induction which states:

$$V = -N\frac{d\phi}{dt}$$

Where

V is the number of volts

N is the number of turns

ϕ is in Webers

t is in seconds

While switching a 0.4 amp 300 volt inductive load, peak voltages of 3,900 volts have been observed[2]. Mil-STD-1399 defines the worst case switching transient for 120 volt ac shipboard systems. The voltage peak is given as 2,500 volts with the wave form as shown in Fig. 2. The source impedance

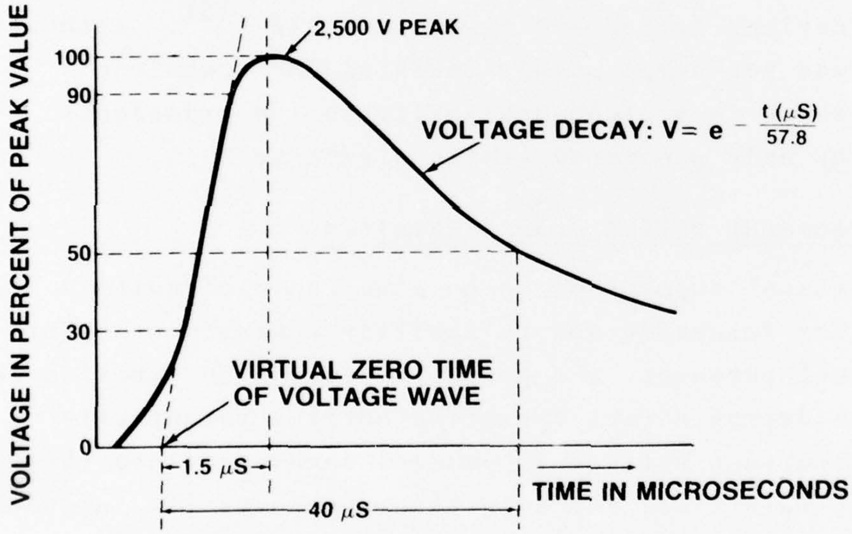

Fig. 2: Mil-STD-1399 Wave form

of this transient is in the range of 16 to 26 ohms[3]. This wave form describes the type of transient which could be produced while switching large inductive loads on board ships, such as hoist and elevator motors. Transients of these magnitudes have also been observed in industrial areas. Studies performed by T. J. Tucker at Sandia Laboratories, have shown that the voltage rise times of static discharges from the human body can be very high, of the order of 1 to 2 kilovolts per nanosecond[4]. Some military groups have adopted a

40 ampere (20,000 volt) upper limit for worst case static discharge threats. Even though the energy content may be relatively low in such a discharge, earlier studies in EMP (Electromagnetic Pulse as generated by an exoatmospheric nuclear detonation) have shown that semiconductor devices are extremely vulnerable to fast rise time transient voltages[5]. The failure threshold level of devices remains an obscure subject with relatively little data available. Occasionally, studies generate information on failure thresholds that is of substantial value. E. VanKeuren of RCA, has described the destructive effects of EMP fast rise time transients on integrated circuits. Device types reported in his study include both bipolar and CMOS. Threshold failure levels in some CMOS devices tested are given in Table 1[6]. Although this work was performed using simulated EMP transient voltages, there is a close similarity to the transients generated by body generated static discharge.

SILICON AVALANCHE DEVICE CHARACTERISTICS

A transient suppressor in an electronic circuit is basically for insurance and reliability enhancement. For all practical purposes, the protector serves no function in the circuit during normal operation until a potentially damaging transient voltage is induced somewhere into the system. At this time, the suppressor performs its intended function which is that of clamping the voltage down to a level below the failure threshold of the circuit or component being protected. The electrical energy in the spike is converted into the heat and subsequently dissipated.

Some of the major electrical parameters of a transient voltage suppressor include: (1) The voltage at which the device attains avalanche breakdown at some defined current level; (2) The circuit operating voltage; (3) The maximum peak pulse current rating of the device; and (4) The maximum clamping voltage of the device under peak pulse current conditions. The product of the maximum peak pulse current

TABLE I

CMOS FAILURE THRESHOLD LEVELS

	PULSE WIDTHS	25nSEC	MINIMUM VALUES 100nSEC	1μSEC
	VOLTS	350	150	60
CD4001A	PULSE CURRENT (AMPS)	10	7	1.2
INPUT	WATTS	3500	1050	72
	MICROJOULES	87.5	105	72
	VOLTS	150	120	20
D4016	PULSE CURRENT (AMPS)	2.0	4.0	2.0
INPUT	WATTS	300	480	40
	MICROJOULES	7.5	48	40
	VOLTS	150	25	12
CD4049	PULSE CURRENT (AMPS)	15	6.0	3.0
OUTPUT	WATTS	2250	150	36
	MICROJOULES	56.2	15	36
	VOLTS	170	60	20
CD4050	PULSE CURRENT (AMPS)	13	7.5	3.0
OUTPUT	WATTS	2210	450	60
	MICROJOULES	55.2	45	60
	VOLTS	120	60	24
CD4050	PULSE CURRENT (AMPS)	4.0	4.0	2.0
INPUT	WATTS	480	240	48
	MICROJOULES	12.0	24	48
	VOLTS	80	150	250
CD4071	PULSE CURRENT (AMPS)	5.2	0.3	0.4
INPUT	WATTS	416	45	100
	MICROJOULES	10.4	4.5	100

and the maximum clamping voltage, is a maximum peak pulse power rating of the device. Since the component is constructed using a silicon pn junction, its temperature coefficent of voltage approximates that of the diffused zener diode.

For general applications, the 1N5629A through 1N5665A series, was the first JEDEC registered series introduced. This device series is designed to offer protection for 5 volt to 220 volt dc circuits. Military qualified JAN and JANTX types are available per MIL-S-19500/500. Breakdown voltage is defined at low currents where the device attains avalanche breakdown. Peak pulse power dissipation for a 1 msec pulse is 1,500 watts for this series. Forward voltage drop is conservatively rated at 3.5 volts maximum for a 100 amp 8.3 msec, one half sine wave pulse.

Table II lists the electrical characteristics of the 1N5629A series. Although the JEDEC registered series is primarily discussed in this paper, there are many other device types offered under manufacturer's in-house numbers which cover a broad spectrum of power rating and operating voltage. There is also a bipolar series which bears the nomenclature 1N6036A through 1N6072A. Silicon devices are rated with a maximum junction temperature of 175°C which is characteristic of this material type. This is due to increasing leakage currents with temperature and well defined upper limits of the reliability of silicon devices. The specific derating curve for the 1N5629 series is shown in Fig. 3. Operating within these limits will maintain a maximum peak junction temperature within a safe margin.

Under manufacturing conditions, as well as specifications, protectors are tested at a given pulse condition. The 10 x 1,000 wave form describes the pulse test for the JEDEC registered device types.

TABLE II - Specifications for 1N5629A Series

JEDEC TYPE NUMBER	GENERAL SEMICONDUCTOR PART NUMBER	REVERSE STAND OFF VOLTAGE V_R VOLTS	BREAKDOWN VOLTAGE BV VOLTS Min	BREAKDOWN VOLTAGE BV VOLTS Max	@ I_T mA	MAXIMUM CLAMPING VOLTAGE @ I_{PP} V_C VOLTS	MAXIMUM REVERSE LEAKAGE @ V_R I_R µA	MAXIMUM PEAK PULSE CURRENT I_{PP} A	MAXIMUM TEMPERATURE COEFFICIENT OF BV %/°C
1N5629	1.5K6.8	5.50	6.12	7.48	10	10.8	1000	139	.057
1N5629A	1.5K6.8A	5.80	6.45	7.14	10	10.5	1000	143	.057
1N5630	1.5K7.5	6.05	6.75	8.25	10	11.7	500	128	.061
1N5630A	1.5K7.5A	6.40	7.13	7.88	10	11.3	500	132	.061
1N5631	1.5K8.2	6.63	7.38	9.02	10	12.5	200	120	.065
1N5631A	1.5K8.2A	7.02	7.79	8.61	10	12.1	200	124	.065
1N5632	1.5K9.1	7.37	8.19	10.0	1	13.8	50	109	.068
1N5632A	1.5K9.1A	7.78	8.65	9.55	1	13.4	50	112	.068
1N5633	1.5K10	8.10	9.00	11.0	1	15.0	10	100	.073
1N5633A	1.5K10A	8.55	9.5	10.5	1	14.5	10	103	.073
1N5634	1.5K11	8.92	9.9	12.1	1	16.2	5	93	.075
1N5634A	1.5K11A	9.40	10.5	11.6	1	15.6	5	96	.075
1N5635	1.5K12	9.72	10.8	13.2	1	17.3	5	87	.078
1N5635A	1.5K12A	10.2	11.4	12.6	1	16.7	5	90	.078
1N5636	1.5K13	10.5	11.7	14.3	1	19.0	5	79	.081
1N5636A	1.5K13A	11.1	12.4	13.7	1	18.2	5	82	.081
1N5637	1.5K15	12.1	13.5	16.5	1	22.0	5	68	.084
1N5637A	1.5K15A	12.8	14.3	15.8	1	21.2	5	71	.084
1N5638	1.5K16	12.9	14.4	17.6	1	23.5	5	64	.086
1N5638A	1.5K16A	13.6	15.2	16.8	1	22.5	5	67	.086
1N5639	1.5K18	14.5	16.2	19.8	1	26.5	5	56.5	.088
1N5639A	1.5K18A	15.3	17.1	18.9	1	25.2	5	59.5	.088
1N5640	1.5K20	16.2	18.0	22.0	1	29.1	5	51.5	.090
1N5640A	1.5K20A	17.1	19.0	21.0	1	27.7	5	54	.090
1N5641	1.5K22	17.8	19.8	24.2	1	31.9	5	47	.092
1N5641A	1.5K22A	18.8	20.9	23.1	1	30.6	5	49	.092
1N5642	1.5K24	19.4	21.6	26.4	1	34.7	5	43	.094
1N5642A	1.5K24A	20.5	22.8	25.2	1	33.2	5	45	.094
1N5643	1.5K27	21.8	24.3	29.7	1	39.1	5	38.5	.096
1N5643A	1.5K27A	23.1	25.7	28.4	1	37.5	5	40	.096
1N5644	1.5K30	24.3	27.0	33.0	1	43.5	5	34.5	.097
1N5644A	1.5K30A	25.6	28.5	31.5	1	41.4	5	36	.097
1N5645	1.5K33	26.8	29.7	36.3	1	47.7	5	31.5	.098
1N5645A	1.5K33A	28.2	31.4	34.7	1	45.7	5	33	.098
1N5646	1.5K36	29.1	32.4	39.6	1	52.0	5	29	.099
1N5646A	1.5K36A	30.8	34.2	37.8	1	49.9	5	30	.099
1N5647	1.5K39	31.6	35.1	42.9	1	56.4	5	26.5	.100
1N5647A	1.5K39A	33.3	37.1	41.0	1	53.9	5	28	.100
1N5648	1.5K43	34.8	38.7	47.3	1	61.9	5	24	.101
1N5648A	1.5K43A	36.8	40.9	45.2	1	59.3	5	25.3	.101
1N5649	1.5K47	38.1	42.3	51.7	1	67.8	5	22.2	.101
1N5649A	1.5K47A	40.2	44.7	49.4	1	64.8	5	23.2	.101
1N5650	1.5K51	41.3	45.9	56.1	1	73.5	5	20.4	.102
1N5650A	1.5K51A	43.6	48.5	53.6	1	70.1	5	21.4	.102
1N5651	1.5K56	45.4	50.4	61.6	1	80.5	5	18.6	.103
1N5651A	1.5K56A	47.8	53.2	58.8	1	77.0	5	19.5	.103
1N5652	1.5K62	50.2	55.8	68.2	1	89.0	5	16.9	.104
1N5652A	1.5K62A	53.0	58.9	65.1	1	85.0	5	17.7	.104
1N5653	1.5K68	55.1	61.2	74.8	1	98.0	5	15.3	.104
1N5653A	1.5K68A	58.1	64.6	71.4	1	92.0	5	16.3	.004
1N5654	1.5K75	60.7	67.5	82.5	1	108.0	5	13.9	.105
1N5654A	1.5K75A	64.1	71.3	78.8	1	103.0	5	14.6	.105
1N5655	1.5K82	66.4	73.8	90.2	1	118.0	5	12.7	.105
1N5655A	1.5K82A	70.1	77.9	86.1	1	113.0	5	13.3	.105
1N5656	1.5K91	73.7	81.9	100.0	1	131.0	5	11.4	.106
1N5656A	1.5K91A	77.8	86.5	95.5	1	125.0	5	12.0	.106
1N5657	1.5K100	81.0	90.0	110.0	1	144.0	5	10.4	.106
1N5657A	1.5K100A	85.5	95.0	105.0	1	137.0	5	11.0	.106
1N5658	1.5K110	89.2	99.0	121.0	1	158.0	5	9.5	.107
1N5658A	1.5K110A	94.0	105.0	116.0	1	152.0	5	9.9	.107
1N5659	1.5K120	97.2	108.0	132.0	1	173.0	5	8.7	.107
1N5659A	1.5K120A	102.0	114.0	126.0	1	165.0	5	9.1	.107
1N5660	1.5K130	105.0	117.0	143.0	1	187.0	5	8.0	.107
1N5660A	1.5K130A	111.0	124.0	137.0	1	179.0	5	8.4	.107
1N5661	1.5K150	121.0	135.0	165.0	1	215.0	5	7.0	.108
1N5661A	1.5K150A	128.0	143.0	158.0	1	207.0	5	7.2	.108
1N5662	1.5K160	130.0	144.0	176.0	1	230.0	5	6.5	.108
1N5662A	1.5K160A	136.0	152.0	168.0	1	219.0	5	6.8	.108
1N5663	1.5K170	138.0	153.0	187.0	1	244.0	5	6.2	.108
1N5663A	1.5K170A	145.0	162.0	179.0	1	234.0	5	6.4	.108
1N5664	1.5K180	146.0	162.0	198.0	1	258.0	5	5.8	.108
1N5664A	1.5K180A	154.0	171.0	189.0	1	246.0	5	6.1	.108
1N5665	1.5K200	162.0	180.0	220.0	1	287.0	5	5.2	.108
1N5665A	1.5K200A	171.0	190.0	210.0	1	274.0	5	5.5	.108

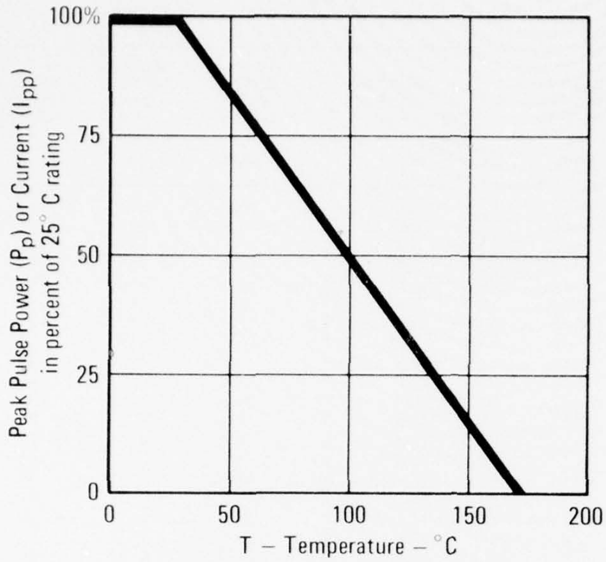

Fig. 3: Derating Curve

Silicon avalanche suppressors are tested at a given pulse condition. Most protectors are tested with an exponential decay pulse which is at one half of the peak value at 1 milisecond and having a rise time of 10 microseconds. This is referred to as a 10 x 1,000 wave form. A current defining the peak pulse power limits for different fall time exponential pulse wave forms, with pulse time defined as the time for decay to one half peak value, is shown in Fig. 4. If the pulse is

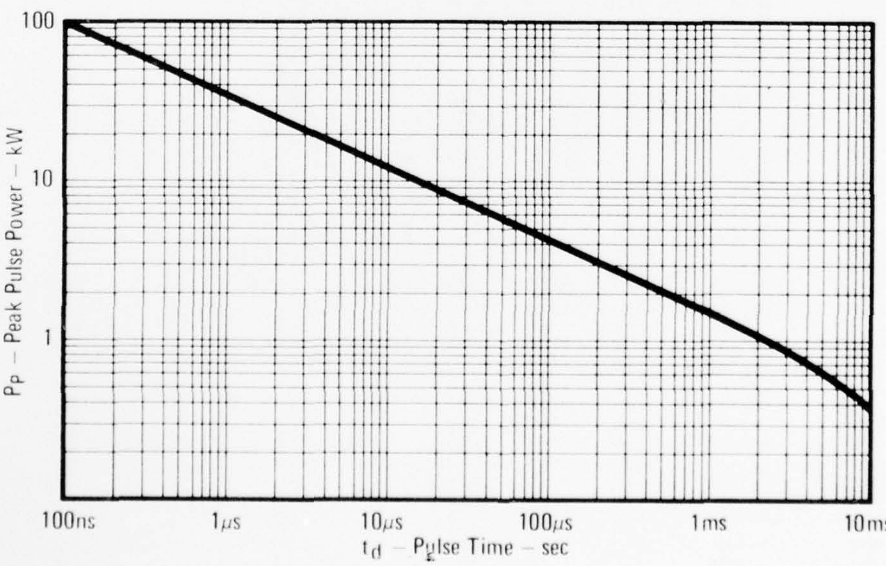

Fig. 4: Peak Pulse Power vs Pulse Time

sinusoidal, derate to 75 percent of the value for the exponential decaying pulse, and 66 percent if the incident pulse is a square wave.

The selection of a device to provide optimum transient suppression in a given circuit sometimes presents a problem to the designing engineer. With Table II as a reference, the following guidelines have been found useful in making an adequate choice of the right suppressor component:

1) Determine the maximum dc or continuous operating voltage which is the nominal circuit voltage plus the tolerance on the high side, giving maximum voltage of the circuit.

2) Select a transient suppressor to have a reverse standoff voltage equal to or greater than the maximum circuit voltage, as defined in 1, above. This selection will allow for operating over a temperature range of $-55^{\circ}C$ to $+ 175^{\circ}C$.

3) Define the wave shape or source of the transient and duration of the pulse. Determine the maximum peak pulse power to be dissipated by the suppressor. If the pulse decays exponentially, define the pulse time for decay to 50% crest value.

4) Check the peak pulse current on the data sheet to assure that it is within the maximum rating of the suppressor for a 1 msec pulse. An example would be the standard 1N5629A (6.8V) device for a current rating of 143A maximum or 100A maximum for the 1N4533A (10V) or 19.5A maximum for the 1N5651A (56V).

5) If the pulse decays exponentially, but different than the 1 msec which is called out on the specifications in the

data sheet, check the "peak pulse power versus *pulse time*" curve in Fig. 4 for pulse duration.

6) If the peak pulse power is within the maximum rating of the suppressor, for example 1.5 kW for a 1 msec, or 6.5KW for a 40 sec exponential decay pulse, use the device as selected. Determine the worst case peak pulse power by multiplying the maximum clamping voltage by the peak pulse current for any given pulse duration.

7) If the pulse is a non-repetitive square wave, derate the suppressor peak pulse power to 66% and for a one half sign wave, derate to 75% of the value for the exponential pulse.

8) If the pulses are a rapidly damped sign wave or rapidly damped square wave, with one time constant within eight cycles, rate the device the same as if the component were subjected to only one pulse as found in 5 and 6 above.

9) If the peak pulse power of the incident pulse is greater than the rating of the suppressor, devices may be stacked in series to increase the power rating for voltages above 10V. An example of this would be, if a 1.5 kW, 100V suppressor is inadequate, then a 3 kW peak power is required. The optimum method to achieve this power level is to stack, in series, two each of a 50V, ± 5% tolerance suppressor.

10) Observe the maximum clamping voltage, which is the product of 1.33 times breakdown voltage. If this is greater than the circuit can withstand, two devices can be stacked in series to reduce clamping factor to approximately 1.15 as compared to the clamping factor of 1.33 for a single device.

ELECTRICAL CAPACITANCE

The electrical capacitance of the silicon avalanche protector is relatively high because of its very large area

junction. The capacitance of a 6V device is approximately 25,000 pf ranging down to about 500 pf for the 200V Type. For dc and low frequency applications, the capacitance presents no serious attenuation; however, for high frequency applications, the methods illustrated in Fig. 5, can be used to effectively reduce capacitance. The low capacitance diode which conducts only in the forward direction can generally be a 1A dc rated high voltage rectifier since these parts are inherently low in capacitance. The main requirements of this component are: (1) that it be able to accommodate the transient current in the forward conduction mode; (2) the breakdown voltage must be higher than the transient suppressor; and (3) the forward voltage drop is reasonably low under peak current conditions.

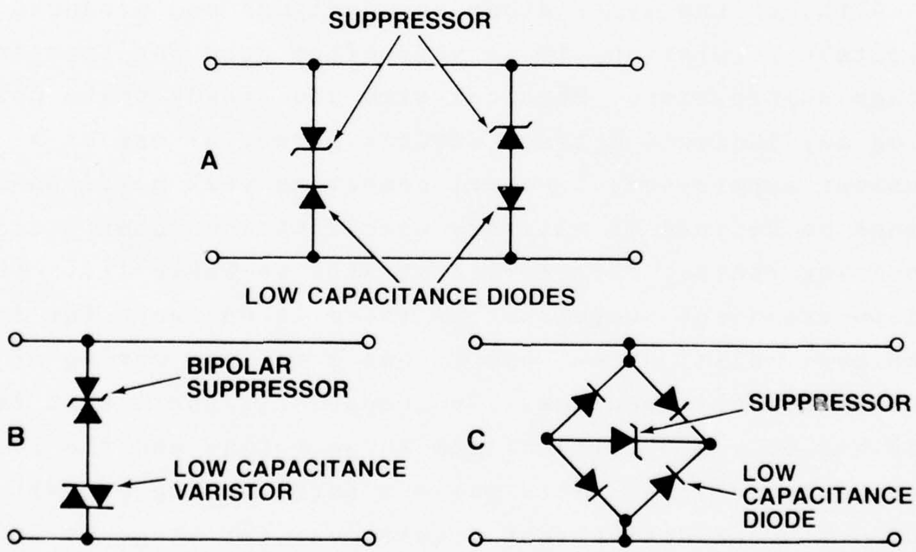

Fig. 5: Capacitance Reduction

INCREASING POWER RATING

Larger, more powerful suppressors can be quite readily manufactured by stacking devices in series, parallel, or series/parallel combinations. The preferred method is series stacking. Devices having voltage tolerances of $\pm 5\%$ share the load almost equally when placed in series. This method

has been proven both in the laboratory and in the field. Custom units can be supplied prepackaged or the user can purchase individual components for assembling a do-it-yourself multiple component part.

Beyond some limit, depending on the applications, it becomes necessary to parallel devices for increased capability. Matching must be performed under pulse conditions with voltages matched as close as 20 millivolts. Very reliable suppressors have been manufactured using both parallel and series/parallel combinations. However, it is recommended that the user himself not perform parallel stacking unless he is thoroughly familiar with the testing methods and is properly equipped to do so.

COMPARING WITH OTHER SUPPRESSORS

ZENER DIODES

Although the zener diode was designed and produced for dc voltage regulation, it is very often used for transient voltage suppression. Physical size and steady state power rating may indicate a zener diode's potential use as a transient suppressor; however, comparing peak pulse power ratings as defined in military specifications does yield some surprising facts. This is illustrated in Table III. The silicon transient suppressor is rated at one watt for steady state power dissipation, but it has a maximum rating of 550 watts at 8.4 milliseconds. By comparison, the 1 Watt Zener Diode has only a 5 watt maximum surge rating and the 50 Watt Zener Diode only 250 watts maximum surge rating per MIL-STD-19500. The production test requirement for surge is 100% for the suppressor, but only on a sample basis for the zener.

TABLE III

PRODUCT	MILS-19500	POWER RATING	SURGE RATING 8.4MSEC	SURGE RATING 1mSEC	TEST FREQUENCY
SUPPRESSOR	434	1W	550W	1,500W	100%
ZENER	115	1W	5W	NONE	SAMPLE
ZENER	406	5W	150W	NONE	TESTED ONCE
ZENER	124	10W	50W	NONE	EVERY
ZENER	114	50W	250W	NONE	6 MONTHS

Comparing the clamping voltage of a zener with a suppressor, again we have a profound illustration between these two components as shown in Fig. 6. Four different 16V devices are compared; three are zeners and one is a suppressor. All devices are lead mounted. The 1 Watt zener diode has only one-tenth of the clamping capability of the suppressor. Also, observe that a 5 Watt steady state glass zener had much less clamping capability than the 1 Watt steady state transient suppressor. The reason for the difference in clamping capability is that the zeners were designed for steady state voltage regulation and the suppressor was designed specifically for absorbing high power transients.

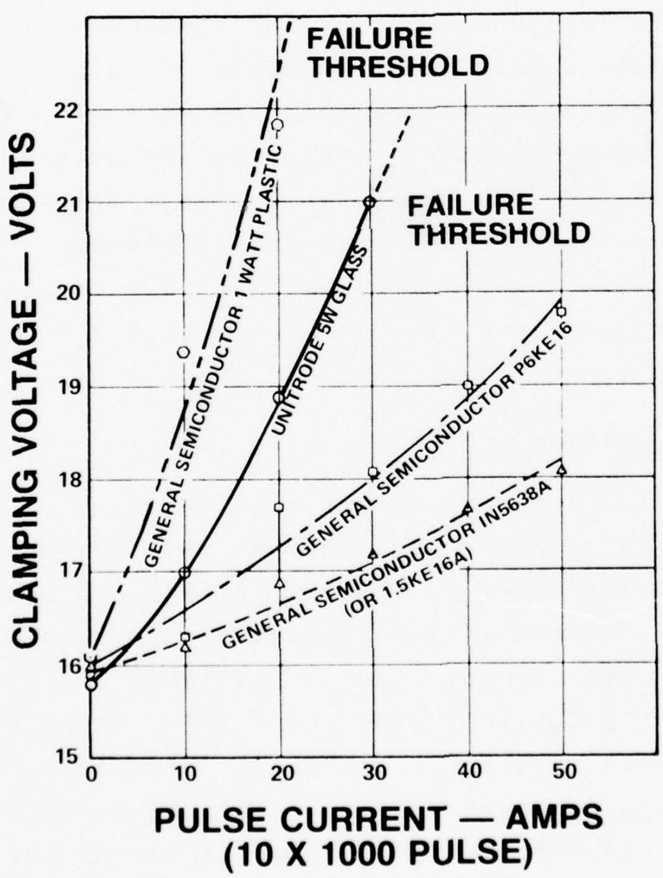

Fig. 6: Clamping Capability of Zener and Suppressor Devices

GAS DISCHARGE PROTECTOR

The gas filled spark gap provides protection while operating in a "firing" mode. The surge striking voltage of these devices is determined by the rise-time of the transient. Most protectors for signal lines are rated in the 90V to 230V range and fire in the range of 500V to 700V maximum under induced lightning conditions. Upon firing, the voltage drop across the device in the arc mode is about 30V. When the current is reduced to a very small amount, the spark gap will restore to the non-conducting mode. In a dc circuit which has an operating voltage above the arc voltage, the use of this device type is not feasible. For ac circuits, a resistor is placed in series with the gas tube to reduce follow-on current and subsequently extinguish the arc when the voltage crosses the zero point. The silicon avalanche component by comparison, does not drop in voltage while providing protection. The chief advantages of the silicon device over the spark gap are fast response and availability of low voltage protection devices. The spark gap, however, is capable of conducting very large currents, in the kiloampere range, for its small size and inherently has a relatively low capacitance of about 1 pf.

METAL OXIDE VARISTOR (MOV)

The metal oxide varistor is a relatively new device which is basically a ceramic-like material having small granules of zinc oxide suspended in a matrix of bismuth oxide. On a curve tracer, the metal oxide varistor resembles a bipolar zener diode. This device type is available in voltage ratings over a relatively wide range from 23V dc through 1200V dc, depending on the type. The metal oxide varistor has a relatively high clamping voltage i.e., the VM33MA1B 23V dc device has a clamping voltage of 55V at 1A and the V130LA10A, for 110V ac, has a clamping voltage of 525V at 100A. An example of clamping capability comparing the metal oxide varistor with the silicon avalanche device is shown in Figs. 7 & 8. Both of these devices are comparable in peak power dissipation.

Breakdown voltage for both types is 68V±5%. These oscillographs were taken under fast rise-time conditions with a square wave pulse having a width of .25 microseconds.

Metal Oxide Varistors are capable of absorbing relatively high peak power for their small size and are economical. The silicon avalanche component has a lower clamping voltage, and is available in the low voltage required for protecting IC and MOS devices.

Fig. 7: 1N5653A, TransZorb™

Fig. 8: GE MOV™ Type 402A

GE MOV™: Registered Trademark of General Electric Company

HYBRID CIRCUIT PROTECTION TECHNIQUES

GAS DISCHARGE TUBE - RESISTOR - SILICON SUPPRESSOR

The gas surge arrestor has the ability to withstand surges in the kiloampere range; however, it is relatively slow in firing, requiring up to several microseconds to go into the conduction mode. The silicon avalanche suppressor has a much faster response time but not the power dissipation capability. Appropriate techniques have been developed to optimize the best characteristics of both protector types. An intervening resistor, inductor, or transformer isolates the devices to allow surge striking voltage to develop across the gas tube under transient conditions. (Without the isolating component the silicon device will clamp the voltage down quite low and the gap will not fire.) The gas tube absorbs the bulk of the energy while the silicon device clips the peak of the residual spike required to fire the gap.

A graph plotting the gas gap dc rated voltage vs the silicon suppressor breakdown voltage is shown in Fig. 9, giving several resistance values for the safe operating area of the system. This circuit has been laboratory tested with transient source impedances over the range of 1 ohm to 100 ohms at General Semiconductor Industries, Inc., and found to be very effective. This set of curves was developed for the 1N5629A series silicon avalanche suppressor and is not applicable for zener diodes.

Resistor isolation is best suited for signal lines where currents are in the milliampere region. For applications where higher currents are required, inductors having values of 500 μH and with a dc resistance of about .5Ω have been found to provide adequate isolation.

CIRCUIT PROTECTION APPLICATIONS

TRAFFIC SIGNAL CONTROLS

G & S Systems of Burlington, Massachusetts, received a Department of Transportation contract to make a study of the most effective protectors for traffic control units for the State of Maine[7]. This effort was initiated because of the lightning threat to intersection traffic signals. The average number of thunderstorms in Maine is 20 per year, with an estimated quantity of 4 transients per year of 600V induced in any line or system.

Among the devices evaluated for this application were a 10 watt zener, a 5 watt lead mount zener and a silicon avalanche protector. The silicon avalanche protector was selected on the basis of cost and performance. The line drivers and line receivers were protected as shown in Fig. 10.

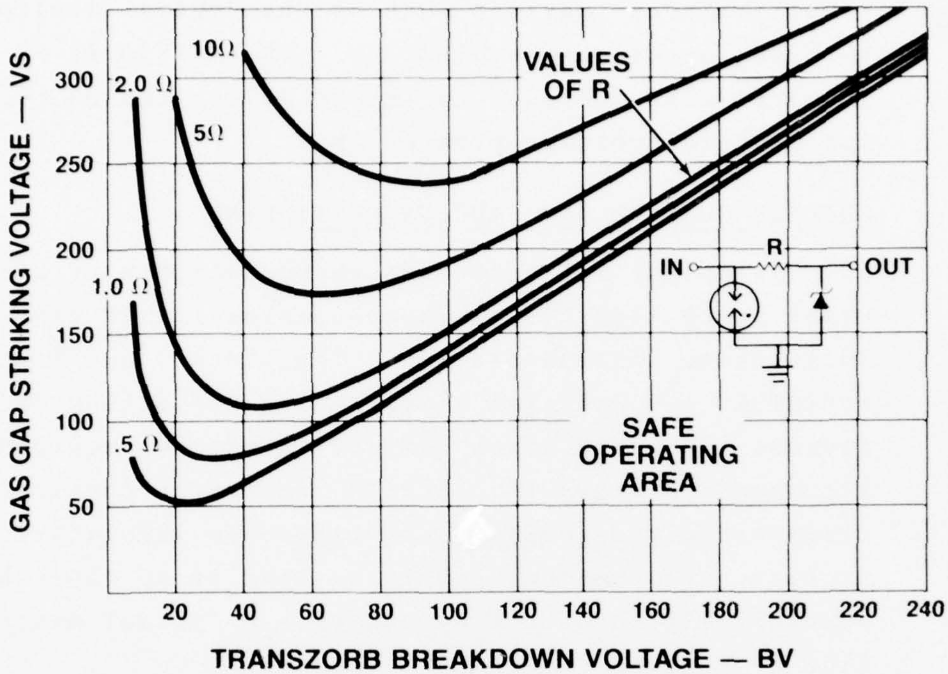

Fig. 9: Safe Operating Area Curves for Combination of Gas Tube Arrestors and Silicon Suppressor.

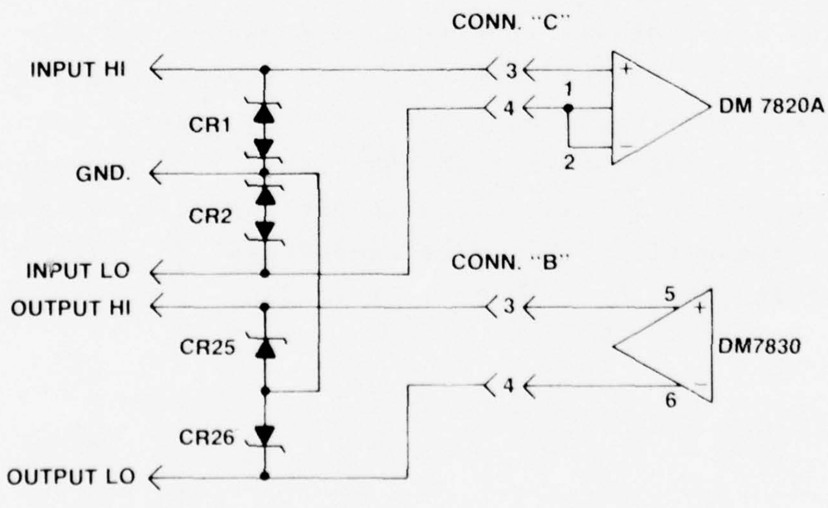

Fig. 10: Traffic Signal Circuit Protection

The DM7820 line receivers operate at a $\pm$20V level and require bipolar devices such as the General Semiconductor 1.5K24C for circuit protection. The DM7830 is 5V logic and requires a device such as the 1N5907 or 1N5908 to provide the low clamping voltage protection.

PROCESS CONTROL AND PROCESS MONITORING

Transient voltages from induced lightning and various other power line disturbrances can easily destroy sensitive solid state instrumentation. The Fischer and Porter manual entitled "A Discussion of Lightning Protection for Electronic Process Instrumentation" discusses various equipment and recommends devices for certain protection applications. These recommendations are based on extensive laboratory and field studies. Protection techniques similar to these have been successfully used by many others. A typical example of signal line protection is shown in Fig. 11.

AIRPORT INSTRUMENT LANDING SYSTEMS

In recent years, the installation of solid state equipment for airport systems has required an improved approach to hardening. Earlier techniques using gas surge arrestors and zener diodes were found inadequate. Recent studies performed by Purdue University and the Georgia Institute of Technology under contract with the Federal Aviation Administration have shown that the TransZorb^{tm} provides adequate [3] protection in many circuits for induced lightning. Included in these efforts is a recommendation for lightning hardening of the AN/GRN-27 Instrument Landing System as shown in Fig. 12.

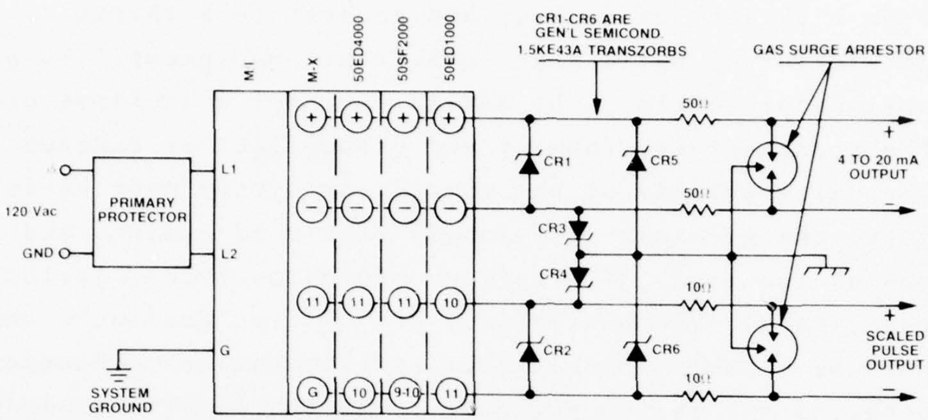

Fig. 11: Signal Line Protection

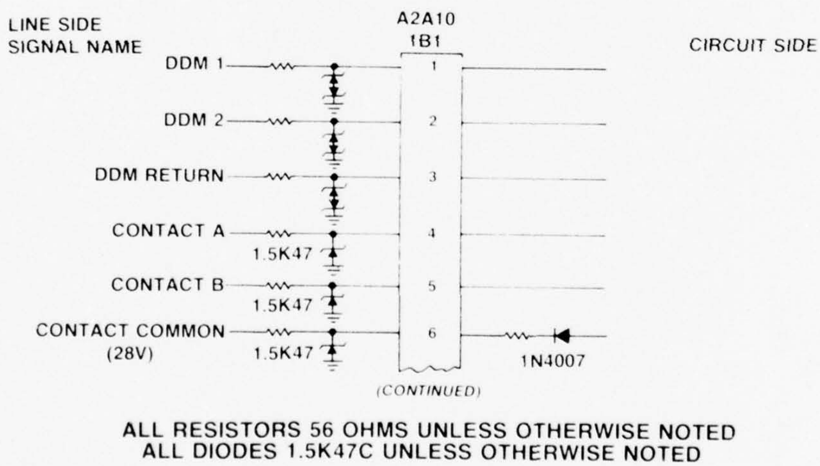

Fig. 12: Typical Terminal Protection for AN/GRN-27 ILS System

CONCLUSION

Potentially destructive transient voltages are generated from a variety of sources and constitute a threat to the new generation of solid state electronic equipment. To provide optimum protection, the design engineer must first define the transient environment and probability of exposure. Next, the vulnerability of the circuit or system must be assessed. Then, the necessary safeguards should be defined and implemented as required. The various protector types, including spark gaps, metal oxide varistors, and silicon avalanche components, each have their capabilities and limitations. However, it behooves the design engineer to be thoroughly knowledgeable of both component vulnerability and protection devices to optimize cost, performance and reliability.

REFERENCES

[1] A Ground Lightning Environment for Engineering Usage; N. Cianos and E. T. Pierce, Stanford Research Institute, McDonnel Douglas Contract No. L. S. - 2817-A3 (1972)

[2] AIRINC Specification No. 413; Aeronautical Radio, Inc. (May 1967)

[3] Private Correspondence with Fred Henrickson, Naval Ship Engineering Center, Hyattsville, MD.

[4] Annals of the New York Academy of Science; Spark Initiation Requirements of a Secondary Explosive, T. J. Tucker, Vol 152, Article 1 (1968)

[5] DNA EMP Awareness Course Notes; Second Edition, IIT Research Institute, DNA Contract No. DASA 01-69-C-0095 (1973)

[6] IEEE Electromagnetic Symposium Record; Effects of EMP Induced Transients on Integrated Circuits, E. Van Keuren (May 1975)

[7] Maine Lightning Project; G&S Systems, Department of Transportation, Contract No. DOT-TSC-686 (1974)

[8] Lightning Protection for Status and Control Lines of AN/GRN 27 Instrument Landing System; G. K. Huddleston, FAA Lightning Protection Study Report No. FAA-RD-75-24 (1975)

EMP TRANSIENT SUPPRESSION

(EMP PROTECTION METHODS USING SILICON AVALANCHE DEVICES)

by

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General Semiconductor Industries, Inc.

Tempe, Arizona

Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

The fast rise-times of Electromagnetic Pulse (EMP) as generated by Exoatmospheric nuclear detonations pose a real threat to semiconductor devices. Threshold destruction levels for some MOS devices have been observed to be as low as 4.5 microjoules. In addition to EMP, induced lightning and switching transients must be suppressed. This paper describes insertion techniques for optimum protection using devices such as the TranZorb^{TM}.

Also, combinations using silicon avalanche devices and spark gaps utilizing the best characteristics of each type are illustrated with supporting laboratory measurements and well defined conditions. The advantages of silicon transient suppressors over the use of zeners is graphically illustrated. Some specific applications in which TransZorbs are being used for EMP transient suppression will be described.

EMP TRANSIENT SUPPRESSION

O. Melville Clark
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INTRODUCTION

When an exoatmospheric nuclear detonation occurs, a very large amount of energy is expressed as gamma radiation. This radiation expands outward from the point of detonation in a sphereical shell. Upon striking the earth's upper atmosphere, compton electrons are generated by the interaction of the gamma rays impinging upon molecules of the rarified upper atmosphere. These electrons are subsequently separated from the heavier ionized atom. The high velocity compton electrons are then influenced by the geomagnetic field with a combination of both events yielding an electromagnetic pulse. Hence, the very high energy, short duration, rf pulse generated is referred to as EMP (Electromagnetic Pulse) and has a duration of 250 nanoseconds and a maximum field strength of 100,000 V/m[1].

The vast majority of semiconductor devices are particularly vulnerable to the fast rise-time transients of EMP origin. Some examples of devices and burn-out energies are shown in the following table[2].

MINIMUM EMP ENERGY TO CAUSE BURNOUT

DEVICE	DESCRIPTION	MINIMUM ENERGY (JOULES)
2N3528	Silicon Controlled Rectifier	$3X10^{-3}$
2N3598	Ge pnp switching Transistor	$3X10^{-4}$
2N4420	Field Effect Transistor	$1X10^{-5}$
MC715	IC Input Gate	$8X10^{-5}$

The SN55107 type line receivers subjected to 200 nanosecond duration pulses have been observed to burn out with as low as 2.8 microjoules[3].

Because of the potential threat to sensitive electronic components and equipment by EMP transients, effective suppression techniques and devices must be employed which are specifically designed to provide adequate protection against this destructive fast rise-time transient exposure.

INDUCTANCE EFFECTS

The fast rise-time voltage transients in circuitry wiring can be a source of high voltage secondary effects, due to what may appear to be virtually negligible inductance in the circuit. This secondary voltage transient is described by the relationship:

$$V(t) = L \frac{di}{dt}$$

Where

L = inductance in henrys

di = incremental current change in amps

dt = incremental time change in seconds

A 1 cm long .03 diameter silver wire "short circuit" was observed to produce a peak pulse secondary voltage of 350 volts under a 200 ampere pulse, having a rise-time of 2.5 nsec.[4]. What is considered normal lead lengths on a transient suppressor device can, under EMP induced voltages, generate relatively high voltages which can result in damage of the circuit intended to be protected. The effects of various lead lengths of a silicon avalanche suppressor transient protection device used in protecting a circuit from a 100A simulated EMP pulse from a 50 ohm source are illustrated in Figs. 1 - 4.

Fig. 1: 3" leads

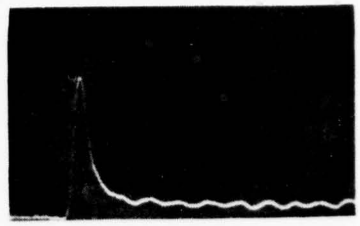


Fig. 2: 1¼" leads

Fig. 3: No leads

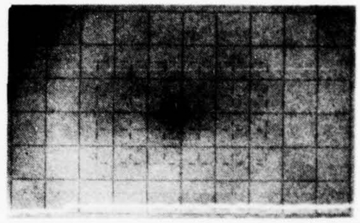


Fig. 4: Disc Package

(All Figs.: Vertical - 200 V/div, Horizontal - 10nsec./div)

These oscillographs have recorded the peak voltage which the protected circuit will see under conditions described below. The energy under each of the curves shown in Figs. 1-4. was computed by integrating the power under the curve with respect to time. This secondary, or transfer pulse energy, as illustrated in Fig. 1 for a device having three inch leads on each end, is 1.5×10^{-4} joules. This is sufficient energy to destroy field effect transistors, IC input gates, and MOS devices and border line for damaging germanium PNP switching transistors. With 1¼" leads, as shown in Fig. 2, the transfer pulse energy due to lead inductance is 7×10^{-5} joules, still sufficient energy to destroy field effect transistors and IC input gates and also MOS devices. With the leads removed, as depicted in Fig. 3, the input placed directly across the device case and insulated tubulation, there is a transfer pulse energy reduction to 6.7×10^{-7} joules. This is below the threshold of destruction for almost all semiconductor devices and graphically illustrates the requirement for appropriate placing of components in the circuitry for optimizing protection capabilities. With the TransZorb*tm repackaged into a disc

*TransZorbtm - Trademark of General Semiconductor Industries, Inc.

which yields virtually no inductance and using low inductance insertion methods in the protective circuit, there is negligible transfer pulse energy and the intended protection is optimized as shown in Fig. 4[5].

The silicon avalanche suppressor device used in this test work was the TransZorb type 1N5645A. The 1N5629A series which covers the range of 5V through 200V was introduced for transient voltage suppression and has found extensive use in suppressing EMP.

TEST INSTRUMENTATION

A block diagram of the pulse testing equipment used in performing tests in gathering data described above and in the balance of this paper is shown in Fig. 5.

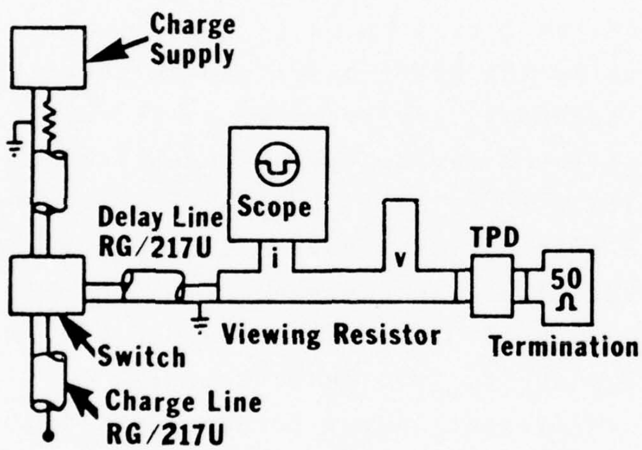
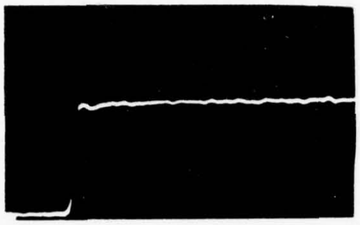


Fig. 5: Instrumentation

This circuit is relatively simple, using a low current, high voltage dc supply, which maintains a length of RG-217/U cable under constant charge. The length of the test pulse is determined by the length of the charge line and the pulse is initiated when the charge line is switched from the power supply to the delay line. The delay line filters out noise and helps to produce a reasonably smooth square pulse. The limitations of equipment used for these experiments is 200 amperes maximum.

RESPONSE TIME OF SUPPRESSOR

The inherent response time of the suppressor tested in this study is extremely fast as illustrated in Fig. 6.

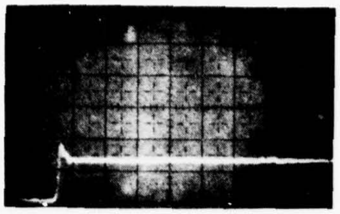


Vertical: 10V/div
Horizontal: 10nsec/div

Fig. 6: Response of 30V TransZorb, type 1N5644A

This depicts the oscillograph of a 30V TransZorb, type 1N5644A clamping a 200A pulse. Rise time of the incident pulse is 4kV/nsec. The insertion methods utilize low inductance techniques to minimize $L\frac{di}{dt}$ effects. Also, the device tested was without the package to further reduce the inductance to illustrate the fast response capability of the basic suppressor junction. The DO-13 industry standard package has an inductance of approximately 10^{-8} henrys which can be significant in some applications.

Efforts to reduce the TransZorb inductance resulted in the development of a product package which resembles the communication type ceramic gas filled spark gap. This is now a commercially available product offered for 6.8V through 100V protection. It is also rated for 1.5kW for 10 X 1000 waveforms. In low inductance insertion fixtures, this device appears to be very effective in providing protection against EMP. The clamping response wave of a 1.5KC device type having a breakdown voltage of 112V at 100A is shown in Fig. 7. The pulse current was 100A, square wave, with a duration of 250 nanoseconds.



Vertical: 100V/div
Horizontal: 10nsec/div

Fig. 7: Response curve of 1.5KC TransZorb Type

CLAMPING CURRENT Vs VOLTAGE

A series of devices were tested to obtain meaningful protection levels offered by the 1N5629A types.

Components were tested under simulated EMP pulse conditions of 40A, 80A and 120A. Curves illustrating the clamping voltages at 70 nsec. for these devices are shown in Fig. 8.

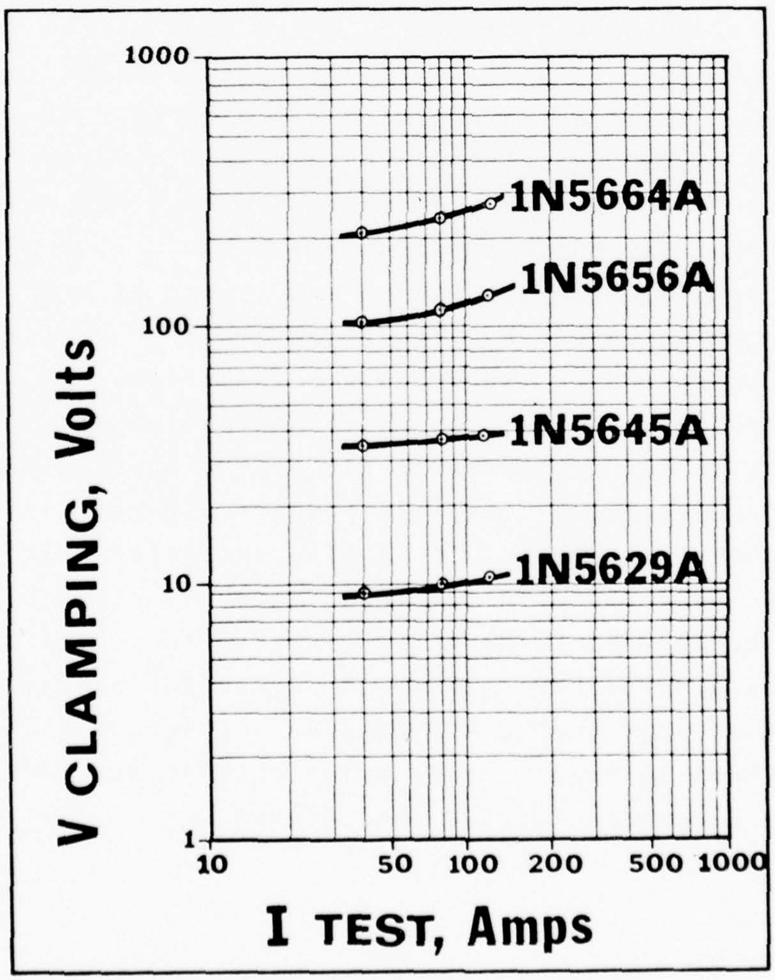


Fig. 8: Clamping Voltage Vs Pulse Current

CLAMPING OF SILICON SUPPRESSOR Vs ZENER DIODE

Both zener diode types and silicon avalanche suppressor devices were subjected to simulated EMP pulses as defined above with currents up through 200A. Again, low inductance insertion techniques were used to minimize inductance in the instrumentation and device's external leads. Clamping voltages for 62V±5% device types are shown in Fig. 9. The planar structured device failed at 200A. Observe that the

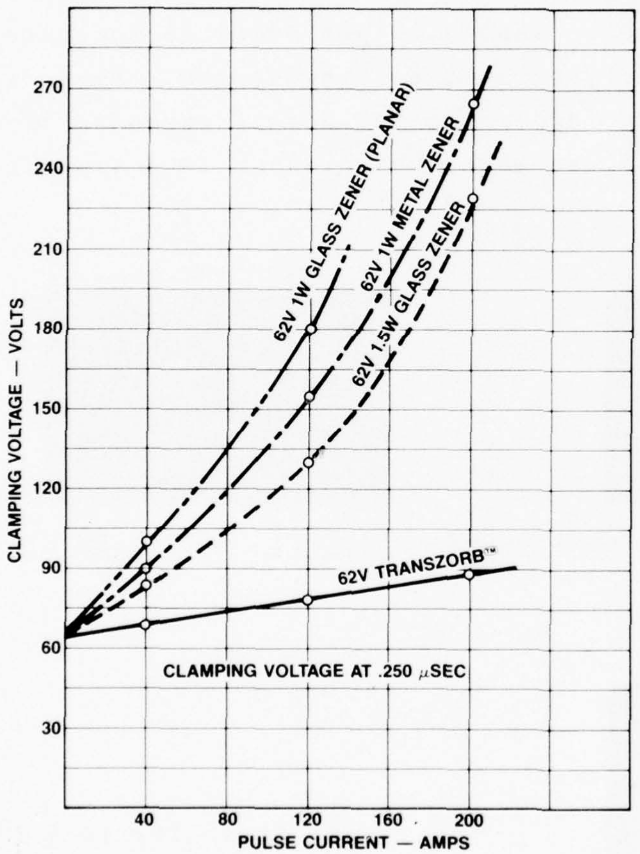


Fig. 9: Clamping Voltage Vs Current for zener and silicon avalanche suppressor

zeners had very high clamping voltages compared to the suppressor device. Although the suppressor has a one watt steady state dissipation, it is specifically designed for transient suppression, hence it presents a superior

performance in this function compared to a zener diode which is designed for voltage regulation.

Both the 1W metal zener and the 1.5W glass zener survived the 200A pulse but with very high clamping voltages of approximately 260V and 230V respectively. The silicon suppressor clamped at about 90V by comparison. Without monitoring the protection provided under actual conditions, the higher clamping voltage of the zeners would have not been observed. From the basis of these results, dynamic tests should be performed to accurately define the capability of a protection device. Figs. 10, 11 and 12 are photos depicting the actual response of the devices described above when subjected to 200A simulated EMP pulses.

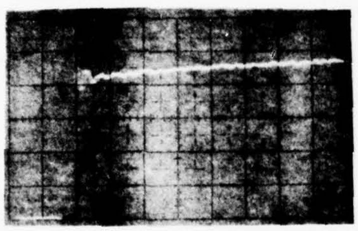


Fig. 10: 62V 1 W Metal Zener

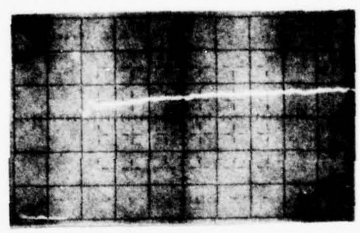


Fig. 11: 62V 1.5W Glass Zener

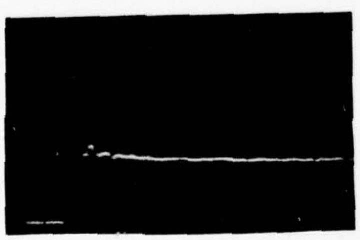


Fig. 12: 62V Silicon Suppressor

For Figs. 10, 11 & 12:

Vertical: 50V/div

Horizontal: 10nsec/div

COMPLIANCE OF SILICON SUPPRESSORS

Silicon transient suppressors are fabricated with large area junctions which is one of the many requirements for high power absorption. Since the junction capacitance is directly proportional to the area, silicon suppressors inherently have a relatively high capacitance. Typical values for the 6V device is of the order of 25,000 pf ranging down to about 550pf for the 200V type at 0V bias. The capacitance is reduced up to an order of magnitude under reverse bias of 90% of the breakdown voltage. A graph showing capacitance Vs breakdown voltage for the TransZorb is shown in Fig. 13. This capacitance can be

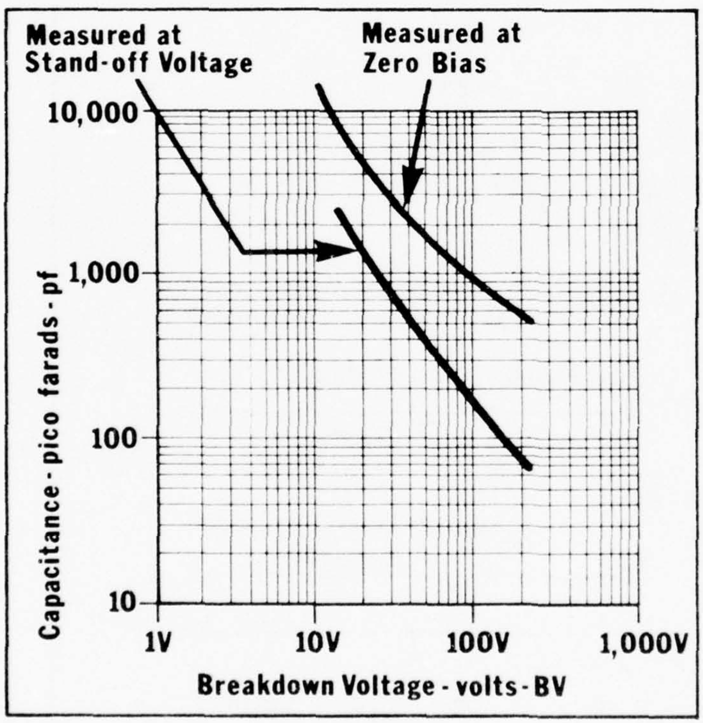


Fig. 13: Breakdown voltage Vs Capacitance

reduced to allow circuit performance into the MHz region with minimal insertion loss. This is accomplished by adding low capacitance in the form of a diode biased in the opposite direction from the suppressor and in series with the suppressor.

Three circuits which have found acceptance have the following boundary conditions for the low capacitance diode:

a. Sufficient pulse rating in the forward direction

b. Minimum voltage drop under high current pulses

c. A reverse voltage breakdown (with margin) exceeding the suppressor breakdown voltage.

d. A sufficiently low capacitance compatible with frequency operation requirements. Low capacitance diodes may be stacked in series to provide further reduction in value.

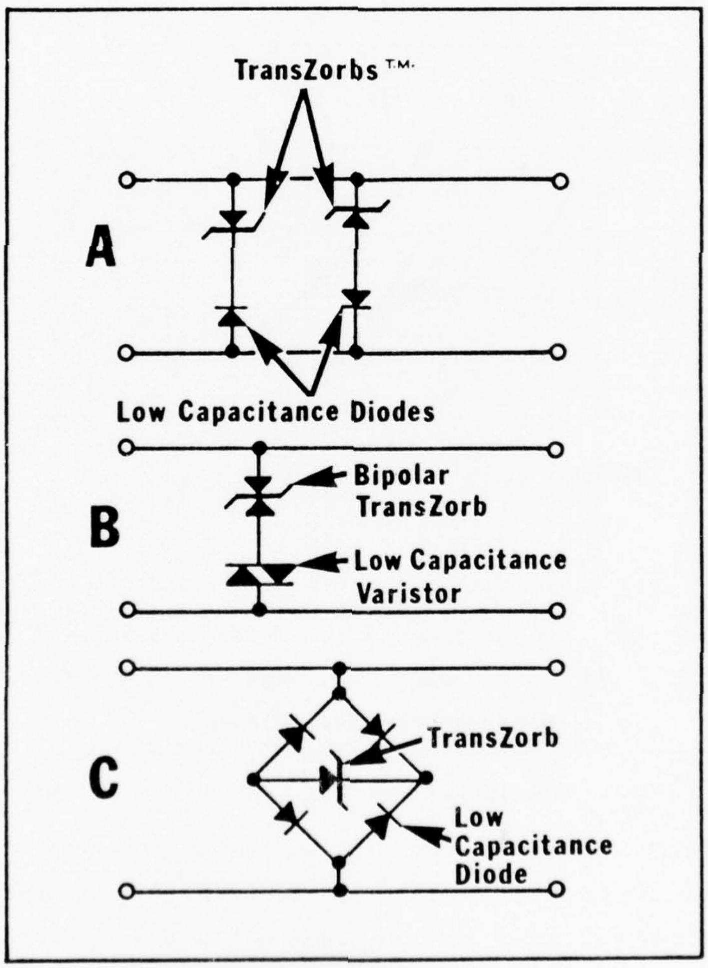
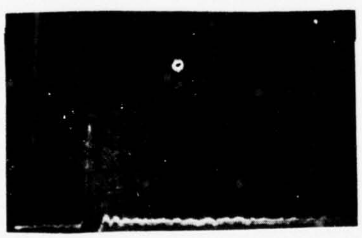


Fig. 14: Capacitance Reduction Circuits

The low capacitance diodes reduce the response time of the protector by the very nature of it's construction. Under pulse conditions, the low capacitance devices by circuit design will conduct in the forward conduction mode only. This action is slower than avalanche mode conduction, requiring approximately 5 nanoseconds for turn-on[6]. Production prototype units have been fabricated for operating in the 10 MHz range while laboratory experimental models have been built with lower insertion losses of less than 0.5 db at 100MHz.

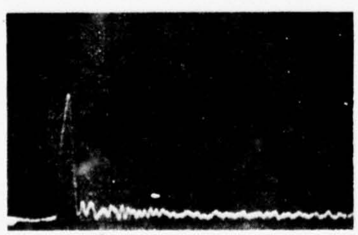
HYBRID PROTECTION CIRCUITS

Gas filled spark gaps have been previously observed to fire and go into full conduction under simulated EMP pulses in less than 5 nanoseconds (6). This is illustrated in Figs. 15 and 16. The incident pulse for each device



Vertical: 500V/div
Horizontal: 10nsec/div

Fig. 15: 70V Spark Gap (CG70)



Vertical: 500V/div
Horizontal: 10nsec/div

Fig. 16: 230V Spark Gap (CG30)

illustrated is 200. Since the gas gaps turn on in less than 10 nanoseconds, some suitable length of cable separating the gap from a silicon suppressor will allow the gap to attain surge striking voltage in a parallel circuit with a low voltage, fast clamping silicon suppressor. Without the isolation,

the silicon device would clamp the incident voltage below the gap surge striking voltage and the gap will not fire. This arrangement will force the more rugged gas device to absorb the bulk of the energy while the fast response avalanche device clips the peak of the pulse admitted past the gap. An illustration of such a protection arrangement is shown in Fig. 17.

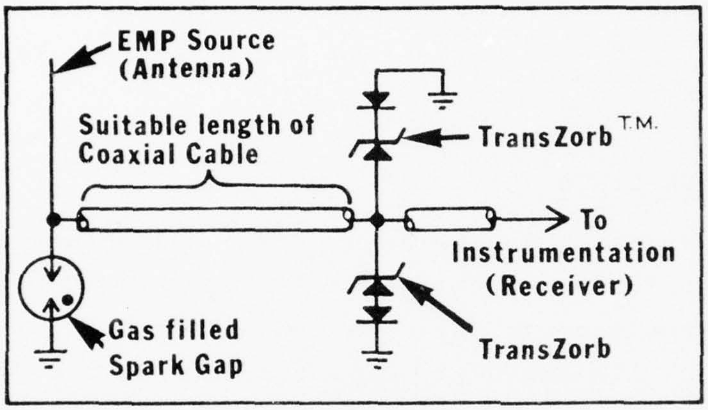
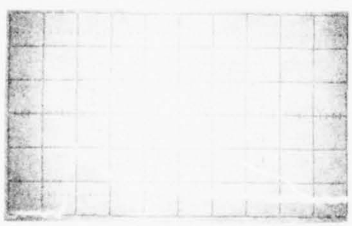


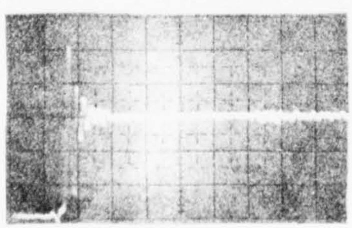
Fig. 17: Cable isolation Protection Circuit

This circuit has been laboratory tested with the CG90 type spark gap which is manufactured by C. P. Clare with response curves as shown in Figs. 18 and 19, with 200A incident pulses.



Vertical: 50V/div
Horizontal: 10nsec/div

Fig. 18: CG90 with 90V Silicon Suppressor



Vertical: 10V/div
Horizontal: 10nsec/div

Fig. 19: CG90 With 30V Silicon Suppressor

The response curve identifies the suppressed pulse as seen by the circuit being protected. The residual pulse shown in Fig. 18 has a CG90 separated from a 90V suppressor by 35 feet of RG-214/U coaxial cable. In Fig. 19 all conditions are the same except the suppressor is clamping at 30V. The suppressor devices used in this system were in DO-13 packages but also in low inductance insertion hardware. The package inductance in the DO-13 was insignificant in this protection arrangement due to the reduction of the input pulse by the spark gap. Inductance isolation of the spark gap and the silicon suppressor has been shown to be effective when the inductance value is relatively small. The circuit shown in Fig. 20 was developed for a balanced line telecommunication circuit. The inductor delays the wave front by reducing the peak and also the slope of the pulse admitted by the gap. Adding a low value resistance to the circuit adapts it for protection against induced lightning.

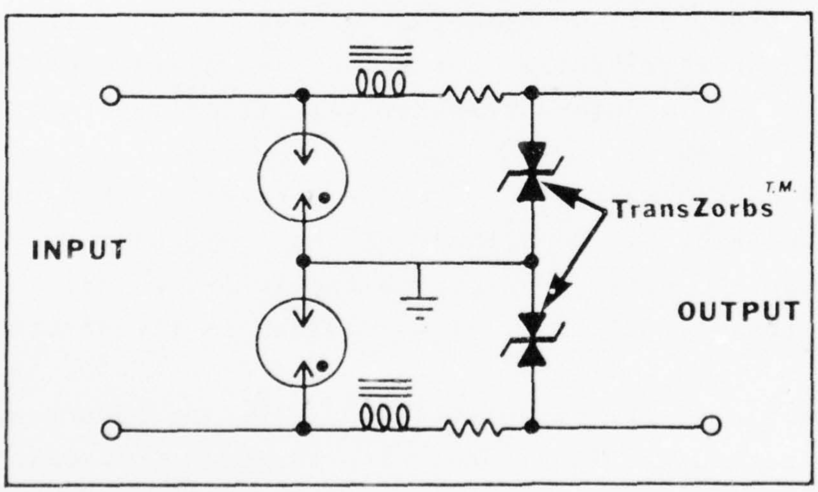


Fig. 20: Inductor Isolation Protector Circuit
(Patent No. 3, 934, 175)

Rf APPLICATIONS

A Terminal Protection Device (TPD) was developed as an outgrowth of an early developmental study with the U. S. Army on the feasibility of using silicon avalanche devices for EMP protection(8). This unit was designed for use in the Pershing Missile Program and is illustrated in Fig. 21. Electrical characteristics include breakdown

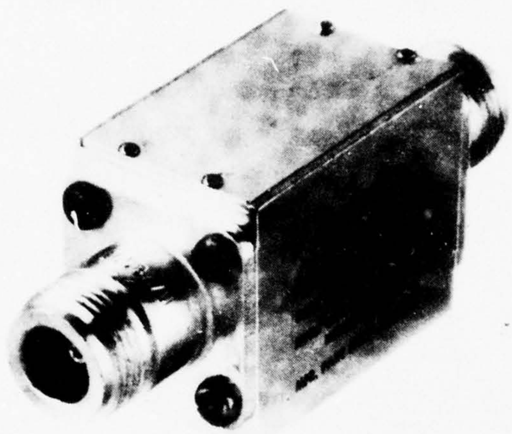


Fig. 21: Rf Terminal Protection Device

voltage of 450V, maximum clamping voltage of 800V within 10 nanoseconds after pulse initiation, and maximum peak "overshoot", or secondary transfer voltage of 1500V with an incident pulse of 200A having a rise-time of 5kV/nsec Subsequent development efforts under contract with Harry Diamond Laboratories, Department of the Army, have yielded a low inductance package which substantially reduces the secondary transfer voltage. This package is illustrated in Fig. 22.

An example of the effectiveness of the low inductance insertion method is illustrated when the pulse attenuation is compared for the two rf TPDs shown in Figs. 21 and 22. Figs. 23 and 24 are the oscillographs of the clamping response curves to a simulated EMP pulse of 200A peak.

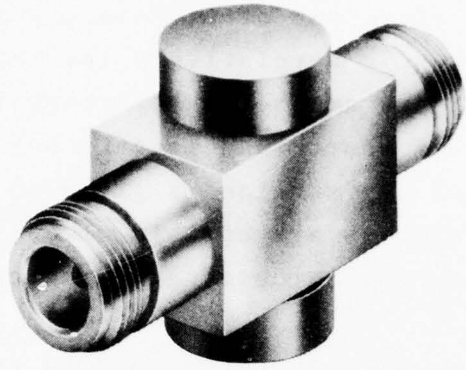


Fig. 22: Low Inductance TPD
(U. S. Patent No. 3, 777, 219)

Both of the devices are electrically equivalent except the low inductance TPD utilizes a special low inductance TransZorb which approximates a disc of .090 in. thick and .300 in. diameter. The 1.5KC ceramic package will fit into the low inductance TPD housing and has been observed to yield minimal secondary or transfer pulse energy from the incident EMP pulse. This was illustrated earlier in Fig. 7.

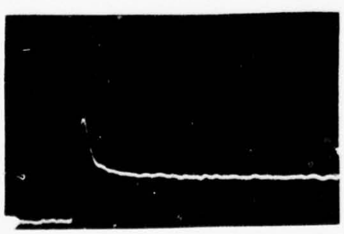


Fig. 23: Rf TPD

Vert.: 500V/div
Horz.: 10nsec/div
(Figs. 23 and 24)

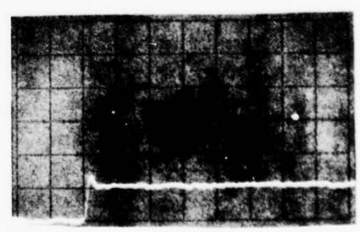


Fig.24: Low Inductance TPD

CONCLUSION

Transient voltage generated by induced EMP presents a unique and sometimes difficult protection problem to the design engineer. The fast rise-time of 5kV/nsec, which can generate multikilovolt spikes in a relatively low inductance circuit, results in a new and healthy respect for the need for maintaining very short lead lengths on protection components. Much lip service is given on protection hardware, but very few are capable of delivering components with test results guaranteeing performance under defined conditions.

Silicon avalanche suppressors have been proven to be effective EMP suppressors. However, as a general rule, there is no one specific component type or device family capable of solving most EMP transient problems. Each situation must be evaluated on its own particular bondary conditions. This should include circuit operating voltage and frequency, circuit destruct threshold, maximum peak current anticipated, and any other pertinent information. Another important aspect is exposure to other transient voltages such as induced lightning or those produced by inductive switching.

When the transient level warrants the requirement, combinations of devices such as the spark gap and the silicon avalanche device can be combined to yield an effective protector against relatively high current transients utilizing the advantages of both device types.

Although the natural tendency is often to use a zener diode, mainly because this technology is well known, one must bear in mind that zener diodes are designed and tested for voltage regulation and fall very short of providing good transient suppression.

The technology exists and components are available for providing EMP protection for almost all applications. It behooves the designer to tap the available resources to equip himself to effectively design and specify EMP protection methods as required.

REFERENCES

(1) DNA EMP Awareness Course Notes, Second Edition, IIT Research Institute, DNA Contract No. DASA01-69-C-0095 p. 1, August 1973.

(2) op. cit. DNA EMP Awareness Course Notes, p. 41.

(3) E. VanKeuren, R. Hendrickson and R. Magyarics, "Circuit Failure Thresholds Due to Transient Induced Stresses", Proceedings of IEEE 75CH1012 4 Mont, p. 500, May 1975.

(4) O. Melville Clark and R. L. Winters, Feasibility Study for EMP Terminal Protection. Harry Diamond Laboratories Contract No. DAAG39-73-C-044, p. 24, 1973.

(5) O. Melville Clark, "Suppressing Conducted EMP Transients", Interference Technology Engineers Master, p. 40, 1973.

(6) O. Melville Clark, "Suppression of Fast Rise-Time Transients", Proceeding of IEEE, 75CH1012 4 Mont, p. 66, May 1975.

(7) O. Melville Clark, "Devices and Methods for EMP Transient Suppression", IEEE EMC Symposium Record, 75CH1002 5 EMC, p. 3A II 51, October 1975.

(8) R. Gadberry and R. Winters, Feasibility Study into the use of TransZorb for EMP Suppression, U. S. Army MERDC Contract No. DAAK02-71-C-0127, November 1971.

BULK ELECTRONIC SURGE ARRESTOR

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

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ABSTRACT

The imposition of EMP hardness and lightning protection requirements on systems in which hundreds or even thousands of lines enter an equipment enclosure presents a serious practical problem because of the very large quantity of protection hardware that is normally required when conventional line-by-line protection techniques are used. Typical of this application are the military tactical switch system and commercial switching equipments. A major improvement has been realized in these applications through the development of a Bulk Electronic Surge Arrestor (ESA). This unique device is a single, compact unit providing lightning and EMP protection of systems in which many signal lines enter sensitive electronic equipment enclosures. The Bulk ESA is normally integrated with an EMI filter pin connector which, in turn, provides improved performance of the Bulk ESA. These two assemblies provide an integrated system which protects against EMP, lightning, EMI, and TEMPEST effects.

1.0 INTRODUCTION

The imposition of EMP hardness and lightning protection requirements on systems in which hundreds or even thousands of lines enter an equipment enclosure presents a serious practical problem because of the very large quantity of protection hardware that is normally required when conventional line-by-line protection techniques are used. Typical of this application are the military tactical switch system and commercial switching equipments.

Compounding the problem in these applications is often a severe lack of space within a small shelter. This lack of space imposes a limitation on the amount of protective hardware that can be included in the shelter, which in turn impairs the effective implementation of electronic surge protection. Also because of this space limitation, tight coupling between input and output lines which partially by-passes the protective equipment has been unavoidable. A major improvement could be realized in these applications if bulk protection of many lines with a single device could be achieved.

Additional problems exist in military applications in which TEMPEST and EMI requirements apply. A general solution to providing bulk EMP and lightning protection should also be compatible with these requirements.

A Bulk Electronic Surge Arrestor (ESA) connector which solves these problems has been developed at GTE Sylvania by Blaisdell and

Tetreault[1]. This device provides substantial protection at the Point of Entry (POE) into the equipment. It is normally integrated with an EMI filter pin connector also properly located at this same point which, in turn, provides improved performance of the Bulk ESA. The installation of these two assemblies provides an integrated system which protects against EMP, lightning, EMI, and TEMPEST effects.

2.0 DEVICE DESIGN

The Bulk ESA is an assembly consisting of two 53-pin hermetically sealed connectors directly interconnected in a sealed chamber which is back-filled with a low pressure argon atmosphere, to which a trace of radioactive tritium is added to enhance fast rise breakdown. A cut away view of the unit is shown in Figure 1. A conductive ground plane member is mounted within the chamber perpendicular to the conductive leads. Each of the leads passes through a different opening in the ground plane and is isolated from it by means of a glass dielectric sleeve. This dielectric spacer is used to center each pin in the ground plane as well as to enhance breakdown at the gas/dielectric interface. An arc can thus occur between each conducting line and the ground plane through which it passes resulting in a compact assembly containing 53 spark gaps.

A second assembly which connects into the Bulk ESA contains a filter pin connector having the proper characteristics for EMI and TEMPEST. The filter on each line also serves to attenuate the high

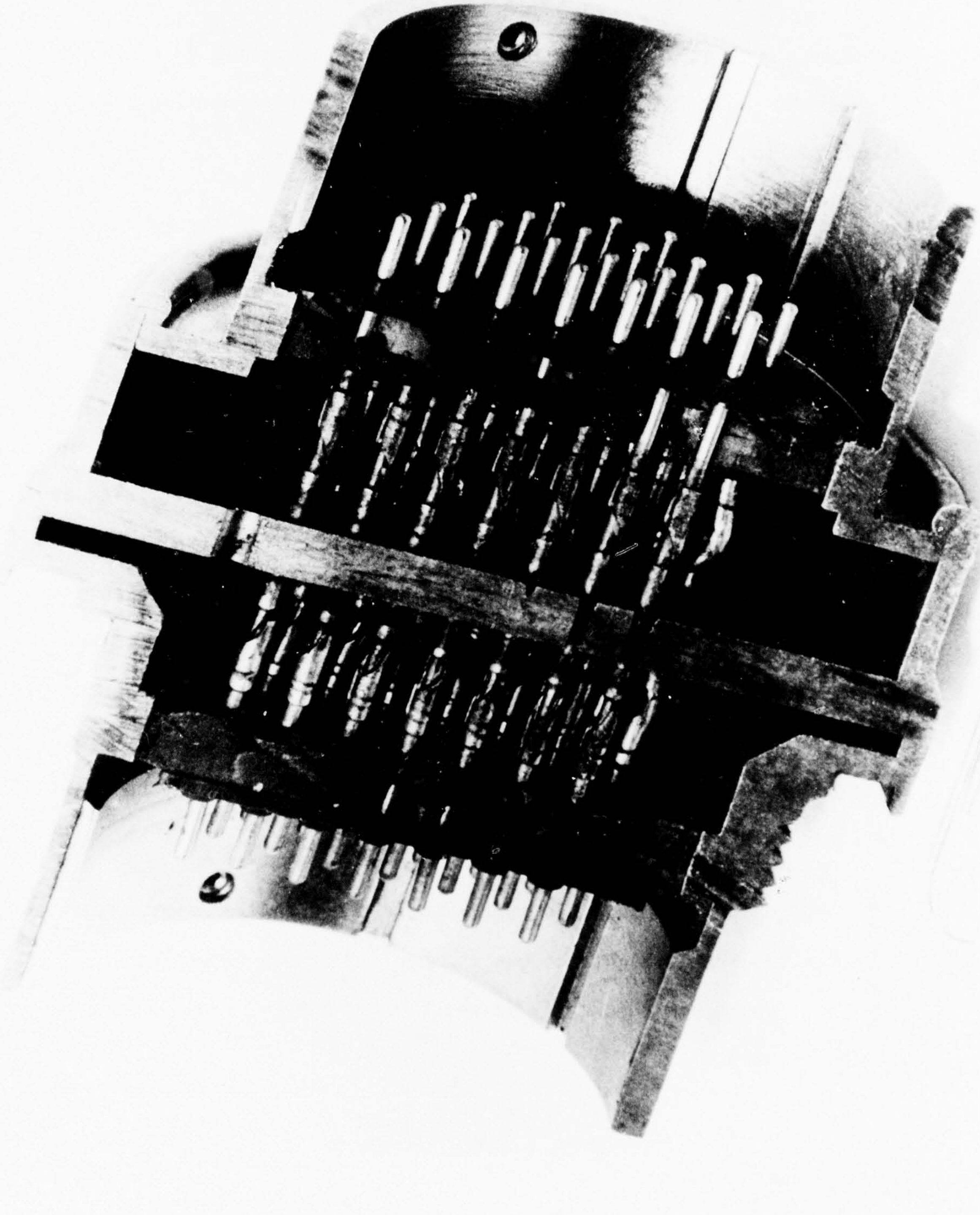

Figure 1: Cross-sectional view of the Bulk ESA

frequency content of any electrical transients appearing in the line through the Bulk ESA. The Bulk ESA and filter pin assemblies are shown in Figure 2.

A typical application of the Bulk ESA is shown in Figure 3. The spark gap assembly is mounted at the point of entry on the inside wall of an equipment shelter and is followed by the filter pin assembly to which the inside shelter cable is then attached.

A number of variations of the existing design are possible. The number of pins (lines) may be tailored to a particular application by the proper choice of connector. Similarly, the cut-off frequency of the filters may be changed by selecting any one of a number of commercially available filter pin connectors. The Bulk ESA and filter pin connector may be made as a single assembly rather than being two assemblies with some resulting design simplifications if the application allows. In short, the basic design described above may be easily tailored to a particular requirement.

The design also provides for a simple preventative maintenance check of the integrity of the gas chamber. A single DC breakdown test on a spare pin checks all 53 spark gaps since all are in a common gas environment.

Figure 2: Bulk ESA and filter pin assemblies

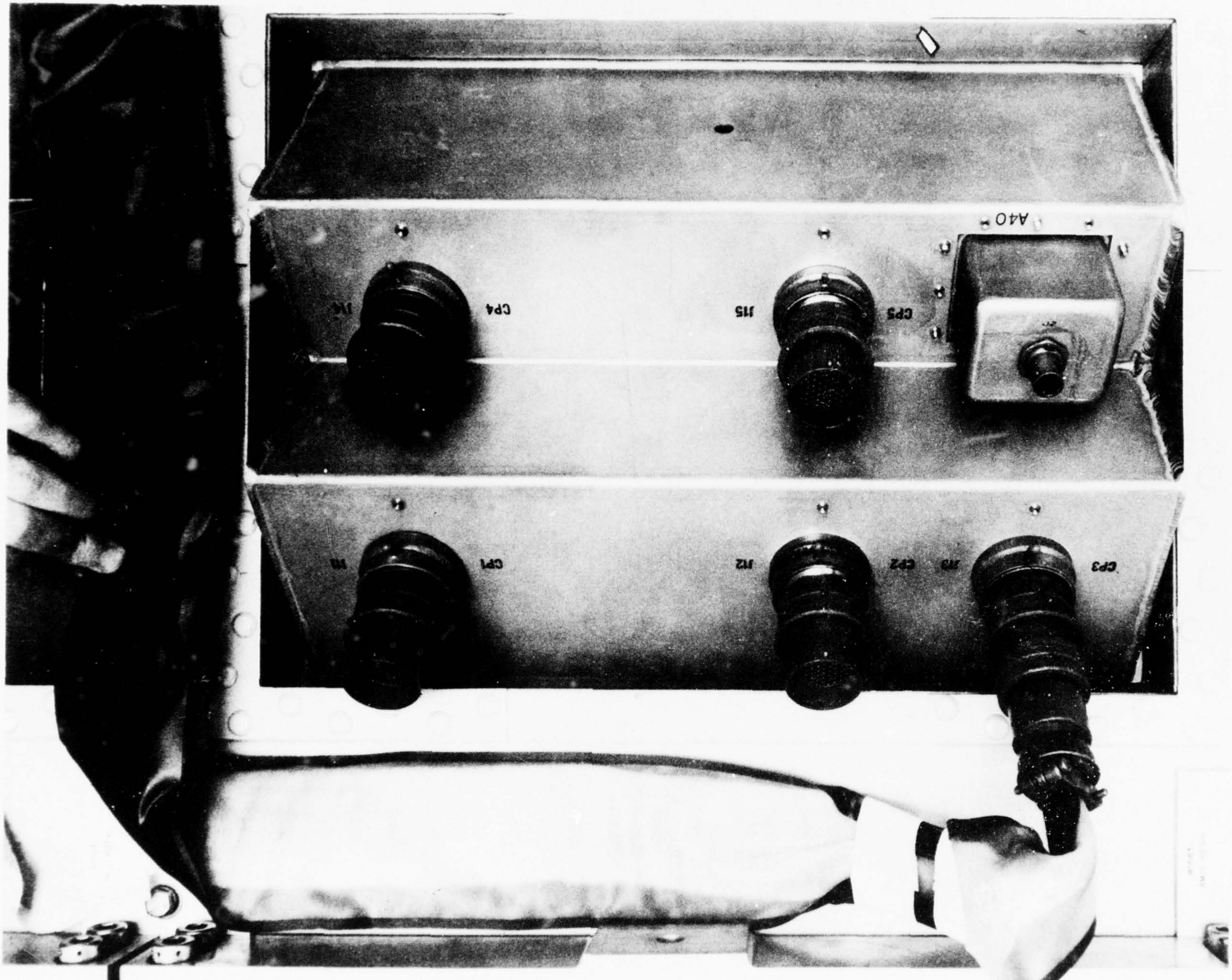

Figure 3: Typical application of the Bulk ESA

3.0 PERFORMANCE CHARACTERISTICS

The electrical characteristics of particular interest in a device of this type are:

1. DC breakdown
2. Fast rise breakdown
3. Current surge characteristics.

The performance of three typical Bulk ESA units in each of these areas is discussed in the following paragraphs.

3.1 DC Breakdown

The basic gas environment used in the Bulk ESA is argon. Radioactive prompting is added to stabilize the pulse-to-pulse response and to minimize the fast rise firing voltage of the arc. The radioactivity has negligible effect, however, upon the DC breakdown voltage of the individual spark gaps. The Paschen curve for an argon atmosphere shown in Figure 4 can then be expected to be obeyed by the Bulk ESA. Conformance with this curve was experimentally verified. For the chosen gap size and pressure, the Bulk ESA DC breakdown voltage was on the order of 225 to 235 volts, the minimum value indicated by the Paschen curve. Operation at the bottom of the Paschen curve was deliberately chosen in order to minimize the effects of spark gap tolerances on individual gap breakdown as well as the sensitivity of the DC breakdown characteristic to changes in chamber pressure.

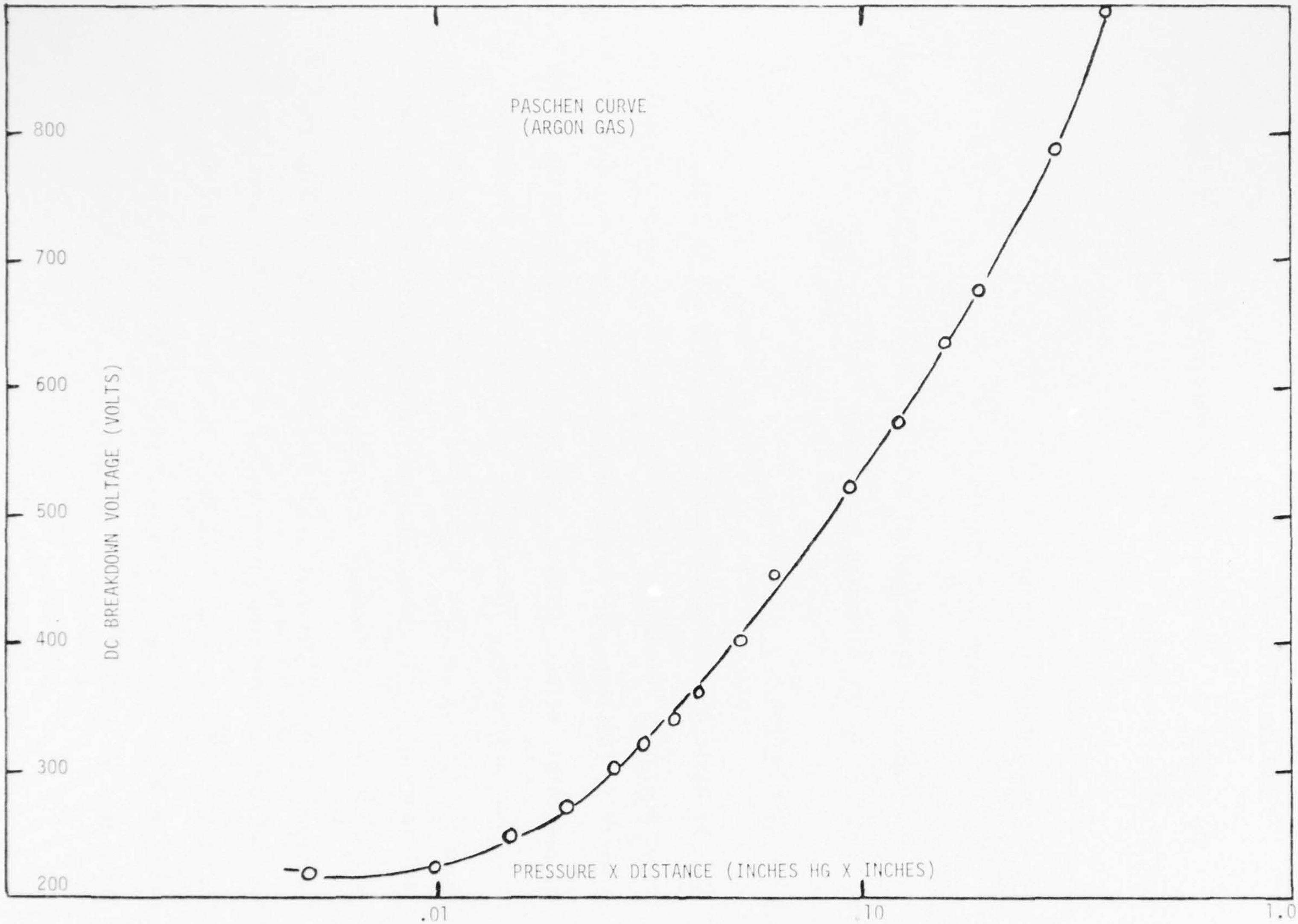

Figure 4: Paschen curve for argon atmosphere and experimental points.

3.2 Fast Rise Breakdown

The fast rise response of the Bulk ESA spark gap was evaluated at rates of 1, 10, and 100 KV/μs. A total of six pins randomly chosen from three Bulk ESA units were each tested ten times one at a time at each of the three rates of rise. The data at each rate of rise thus represents a statistical sample of 60 firings. The results of these tests are plotted in Figure 5. Also shown in this figure for comparison purposes is the specification for a typical commercially available button type spark gap, which is a small single element surge arrestor manufactured by a number of companies for single wire protection.

The highest, lowest, and average fast rise breakdown values observed for the Bulk ESA are indicated by the letters H, L, and A, respectively, while the dashed curve connecting the B's represents the button gap data. As shown, the average fast rise breakdown performance of the Bulk ESA exceeds the button gap performance at each tested rate of rise.

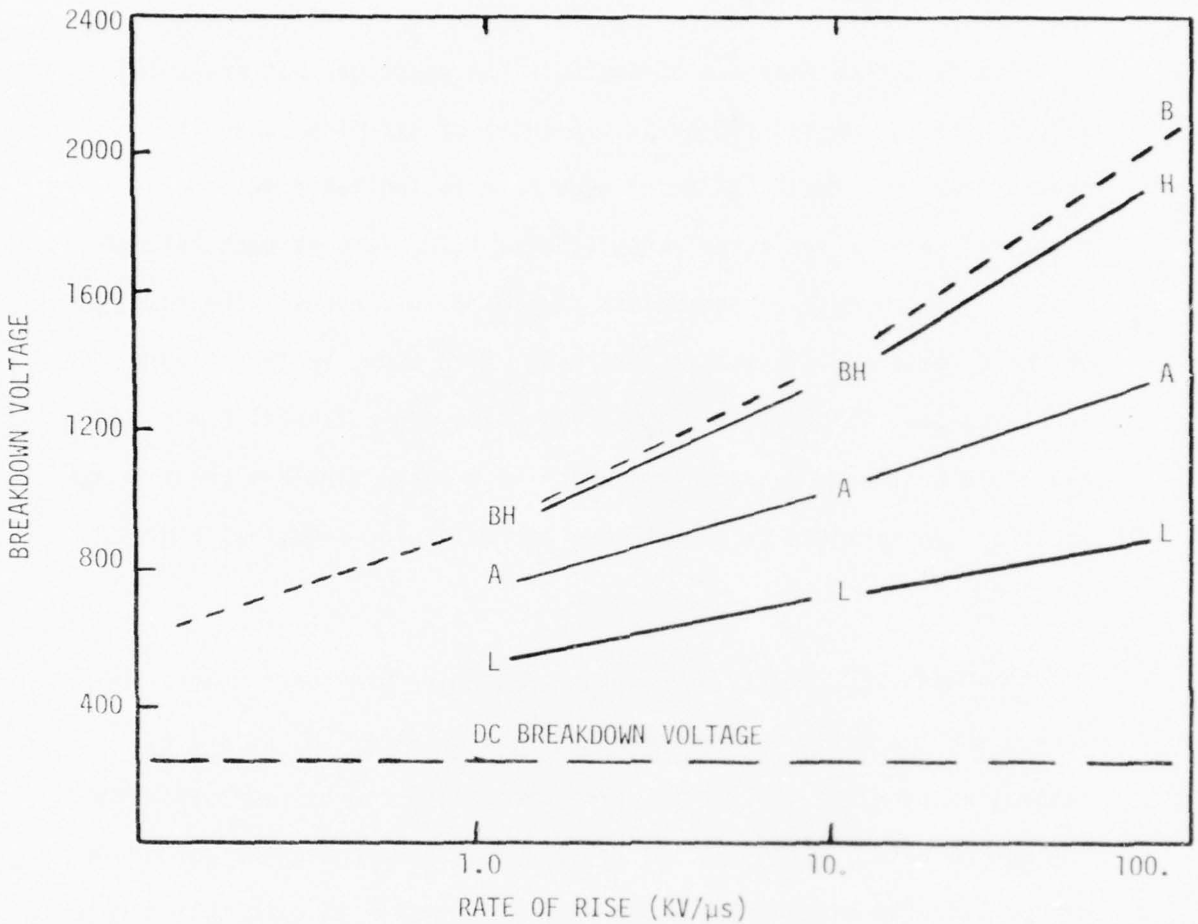

Figure 5: Rates of rise on six randomly selected pins.

In practice, instead of one pin being pulsed at a time, many will be driven simultaneously by an EMP or other electrical transient. In this case, the first gap to fire stimulates breakdown of the other gaps since all are in the same gas environment, minimizing the statistical characteristics of the gas breakdown phenomenon. Consequently, in practice the fast rise firing characteristics will tend toward the lower solid curve in Figure 5.

3.3 Current Surge Characteristics

Current surging of the Bulk ESA was successfully carried out with up to 50,000 ampere current surges having total charges of 1.6 coulombs. Although the pin-to-ground insulation decreased after surging, no evidence of opening or shorting of lines was observed during these tests. These surge measurements were made by driving all 53 pins of the Bulk ESA simultaneously through 2.5 ohm resistors. The current waveform was generated by the discharge of energy stored in an 84 microfarad capacitor bank. The 2.5Ω resistors were used to prevent the firing of one gap from shorting out the other gaps. In practice, this isolation is provided by the impedance of the cable connected to the ESA. The average value of the DC breakdown voltage after current surges of 25,000 and 50,000 amperes is presented in Table 1 for three typical Bulk ESA units.

TABLE 1

Current Surge Characteristics

	Average DC Breakdown Voltage		
Current Surge	ESA No. 15	ESA No. 16	ESA No. 17
Presurge	232 Volts	231 Volts	240 Volts
25000A	219	223	228
50000A	213	220	221
50000A	212	220	215

In conjunction with surge tests conducted on the entire Bulk ESA connector, the current surge handling capability of a single Bulk ESA pin was tested. These tests showed that individual pins are capable of handling 10 x 20 μs* current surges of at least 5000 amperes without failure.

*) 10 μs risetime and 20 μs falltime.

Reference

1) L.L.Blaisdell and N. E. Tetreault, U.S.Patent No. 3,992,652.

HIGH ENERGY SOLID STATE ELECTRICAL SURGE ARRESTOR (ESA)

(SOLID STATE ELECTRONIC SURGE ARRESTOR (ESA))

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

In this paper an engineering model of a high energy (20~40 coulombs of charge, 15~35 Kj) solid state Electrical Surge Arrestor (ESA) is presented. The basic elements are commercial or custom made Metal Oxide Varistors (MOV). The approach to achieve a high coulomb ESA is to use paralleled MOVs with efforts concentrated on ensuring even current partition by matching the MOVs conduction characteristics and using balast resistors. The unit with custom made large area MOVs survived consecutive 40 coulomb surges of 5 ms exponential decay. The peak current was 6.5 kA at a clamping voltage of 1.1 KV. Design consideration, screening techniques, packaging, and test results are reported. A brief review of the MOV physics is also included.

1.0 INTRODUCTION

Military electronic systems are subjected to large electrical surges generated by lightning and nuclear events. To protect these systems Electrical Surge Arrestors (ESA) are needed. State-of-the-art ESAs employ specially designed spark gaps as the primary voltage limiting elements. However, since a large surge current causes intense local heating by ion bombardment, surface spot erosion results in the gap. Also the gas is contaminated by the impurities blasted off from the electrodes and the surrounding insulation materials. All these factors contribute to an aging effect which change the breakdown characteristics of the gap. Moreover, one major limitation of the spark gap is that the breakdown reaction time is not fast enough to meet the stringent requirements of nanosecond threats.

To overcome these problems, a high energy solid state ESA making use of custom-made Metal Oxide Varistors (MOV) as limiting components to replace spark gaps is proposed and studied. The MOV is intrinsically a fast acting device with response time less than one nanosecond. Thus any fast rate of rise breakdown requirements and repeatable characteristics can be easily met. Naturally the solid state ESA using MOVs is not without drawbacks. The most significant limitation of this approach is that the present MOVs can handle only fractions of a coulomb of charge. Also they are suitable to low frequency applications only because of their intrinsically high dielectric constants (~1500).

Since a single 20 - 40 coulomb MOV is not feasible at present, the approach to achieve a high coulomb ESA is to use paralleled MOVs with efforts

concentrated on ensuring even current partition by matching the conduction characteristics of paralleled MOVs and using ballast resistors. In this paper an engineering model of a solid state ESA using custom-made large area MOVs is discussed. Design considerations, packaging, and test results are reported.

II. MOV CHARACTERISTICS

Before presenting the engineering details of the solid state ESA a brief review of the MOV physics is in order. The MOVs are ZnO - based ceramic devices[1] that are made by a pressing and air-sintering process. When biased in either direction the multi-junction device exhibits a highly non-ohmic Zener-like behavior in the I-V characteristics. A fundamental property of the ZnO varistor is that the varistor breakdown (conduction) voltage is linearly proportional to the device thickness for a given powder mix and sintering process[2].

The non-linear characteristics of the MOV device can be characterized by a semi-empirical equation

$$I = KV^{\alpha}, \tag{1}$$

where K is a constant and α is a non-linear exponent usually in the range of 30 - 50.

The MOV conduction mechanism has been studied by a number of researchers[3-9]. Levinson and co-workers[3] believed that it is due to the quantum mechanical (Fowler-Norheim) tunneling effect. However, the physical picture of the MOV conduction phenomena has not been fully understood. More information on the electrical properties of the MOV can be found in Ref. 4 to 9.

Following Matsuoka's simple model of the MOV microstructure, the MOV device can be viewed as a big collection of mini-capacitors connected in parallel and in series, as shown in Figure 1, which are formed by the conducting ZnO grains idealized as cubes of sides d separated by a thin dielectric layer of thickness t. Due to the thinness of t the effective dielectric constant is extremely large, about 1500. Thus the MOV is intrinsically a high capacitance device, which is not desirable in high frequency applications when a large number of paralleled MOVs are required in use.

It was recently found by the authors that when subjected to a dc bias at large currents, the MOV exhibits a second-breakdown accompanied with a thermal runaway[9] (Figure 2). In this dc failure mode no visual physical damage was seen. We believe that the second-breakdown is a bulk thermal effect rather than electronic in nature, since the device could survive KA peak current surges of short duration ($\sim 20 \mu s$) without second-breakdown, and the second-breakdown occurred at a much higher dc current when the device was placed in liquid nitrogen.

All MOVs stressed into second-breakdown showed permanent changes in their I-V characteristics. The most dramatic change was the loss of bipolar conduction symmetry and the degradation of non-linearity, as shown in Figure 2. One possible explanation for this is that the insulating layers in the microjunction have become permanently polarized by the strong field when the material is over-heated by the dissipated energy which might have resulted in a phase change.

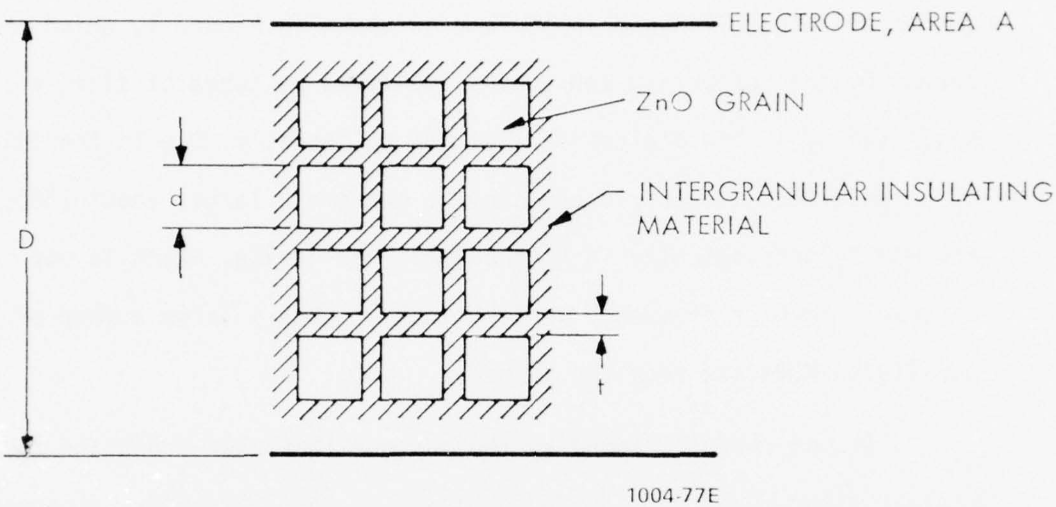

Figure 1 - Idealized model of the MOV microstructure.

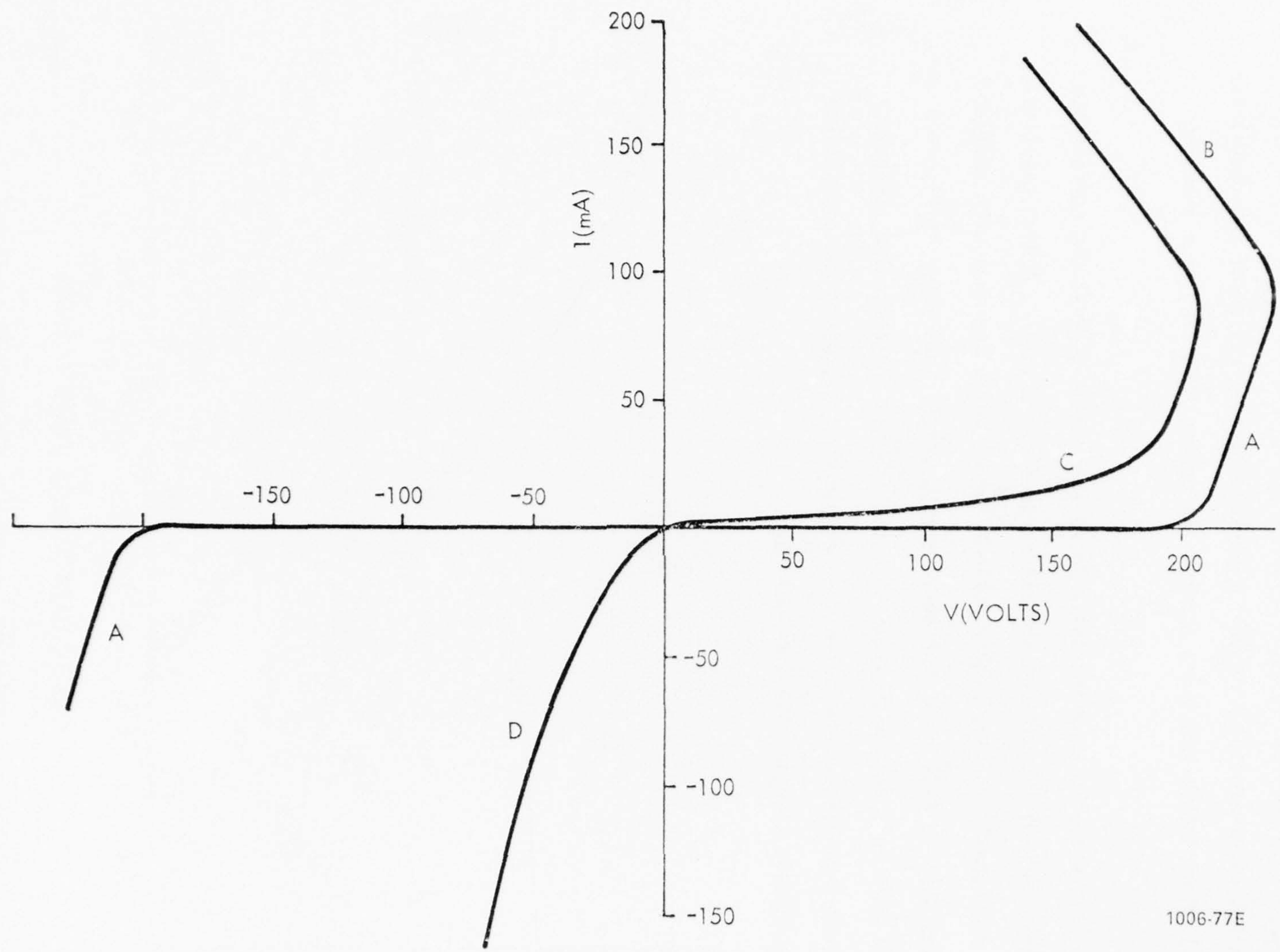

Figure 2 - (a) Typical Zener-like I-V curve of a GE MOV130 varistor. (b) Second-breakdown associated with a thermal runaway observed in a dc test. (c), (d) Non-symmetric conduction of a degraded MOV after second-breakdown.

When surged by large currents, a typical failure mode of the MOV is a hot spot, leading to either a darkened glassy region of low resistance (2KΩ) or a pinhole punctured through the device resulting in a shorting path.

It was also experimentally found that there is a strong correlation between the MOV capacitance and its surge failure level. A high capacitance MOV can usually survive higher coulomb surge, while the ones with smaller values tend to fail at a much lower energy level. As shown in Figure 3 forty MOVs were tested to yield the statistics. This finding suggested a simple non-destructive selection technique, i.e., using the capacitance measurements to eliminate the weak MOVs.

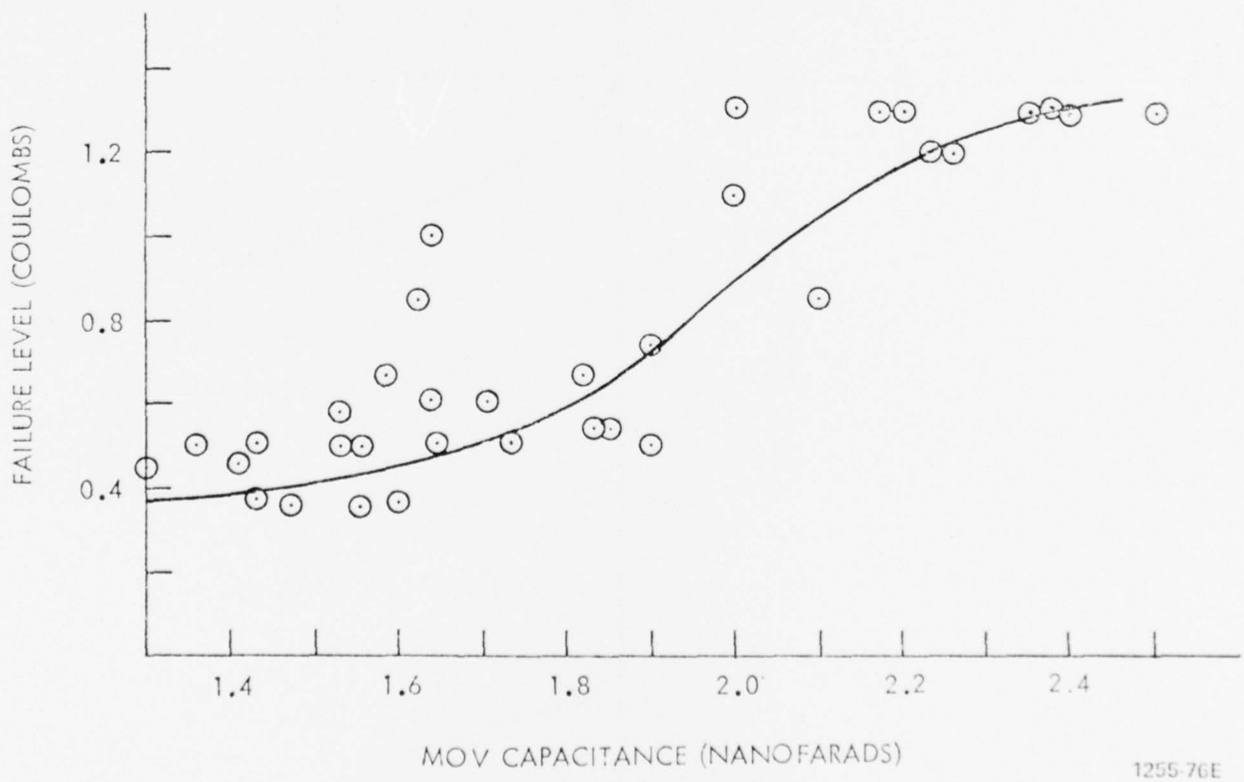

Figure 3 - Correlation between the MOV failure level and the MOV capacitance. The samples tested were GEV130LA20 MOVs.

IV. ESA DESIGN

Since the MOVs must be connected in parallel to have required energy handling capability, it is important to have even current sharing among the branches during the surge. Due to the high non-linearity, small differences in device characteristics cause severe uneven current sharing, thus reducing the total ESA charge handling capability. This problem is largely alleviated by using ballast resistors. As shown in Figure 4, the MOVs were individually balanced by the same amount of resistance R, so that each branch was stabilized by a common load line. To be effective the value of R was chosen is such a way that the voltage drop across it was a sizable fraction of the MOV voltage. Tests showed that this scheme had substantially improved the current sharing.

For the prototype ESA custom made large area MOVs fabricated by Matsushita (Japan) were used. The large area MOV is an annular disk, 8.1 cm O.D., 1.2 cm I.D. and 0.5 cm in thickness. The electrode was a rough textured silver substance. The edges of the disc were covered with insulating epoxy to prevent high voltage arc-over. The varistor's clamping voltage was 550V at 1 mA, and 600 ~ 800 V at 1 kA.

The devices were screen-tested with the GTE Sylvania 5/200K pulser, as shown in Figure 5, which has the following characteristics:

GTE SYLVANIA 5/200 K PULSER

Output Voltage:	0-5000 volts
Maximum Energy Storage:	0-232 kilojoules
Maximum Storage Capacitance:	16,500 microfarads
Maximum Charge Storage:	83 coulombs

The custom made MOV passed 12 coulombs successfully, but failed at 13.5 coulombs. The failure mode was a pinhole, as commonly observed in failures of smaller varistors. A typical surge response of this device is shown in Figure 6.

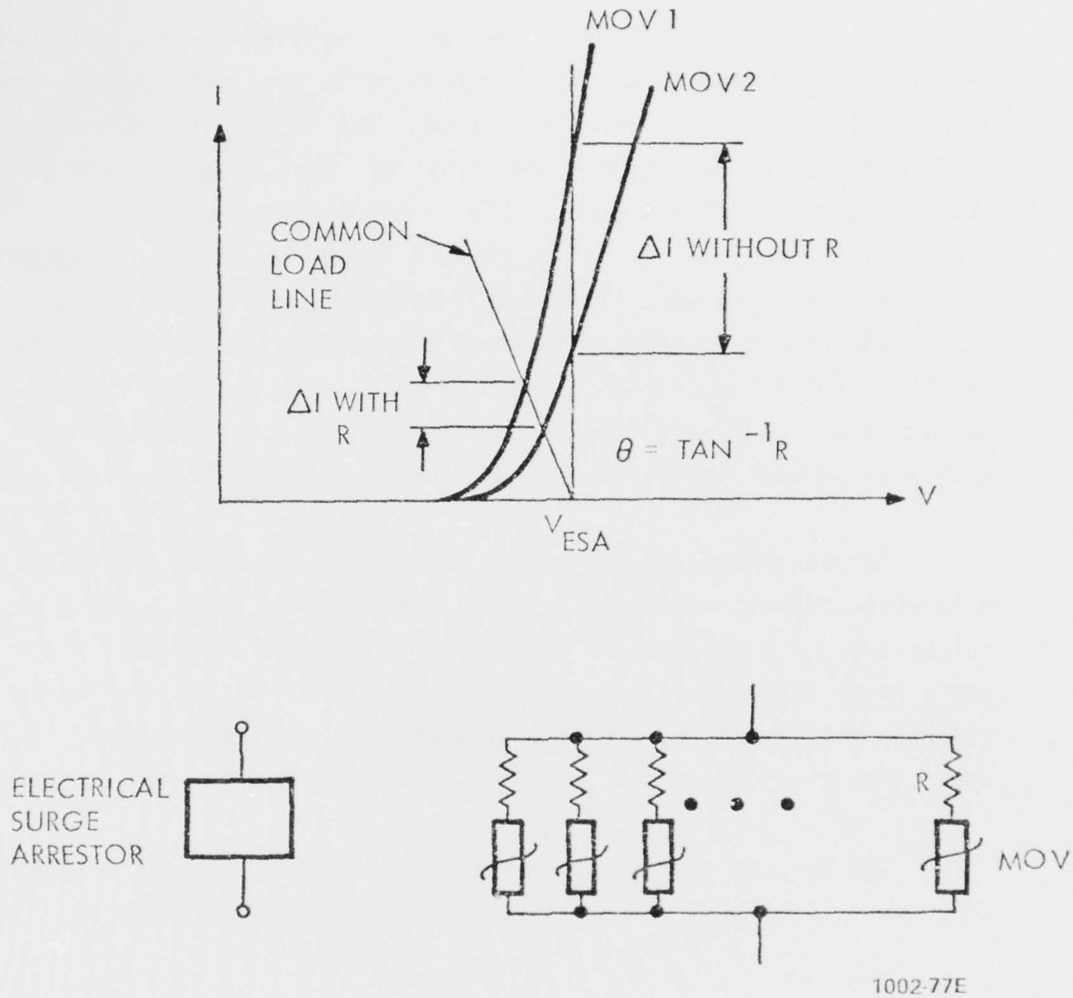

Figure 4 - To achieve a more uniform current sharing, each MOV branch was stabilized by a ballast resistor R.

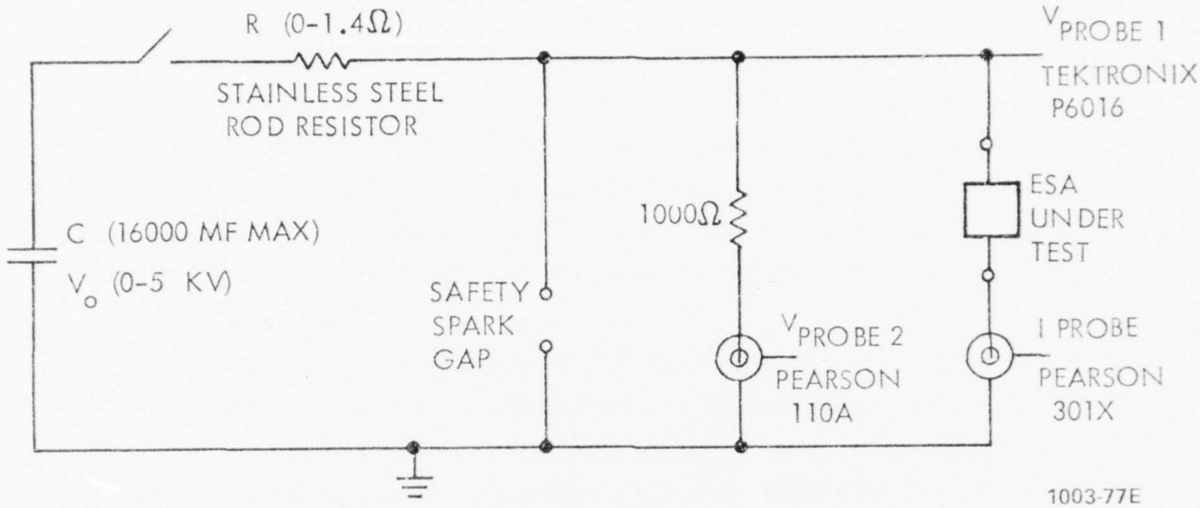

Figure 5 - Schematic of the 5/200K pulser for high coulomb tests.

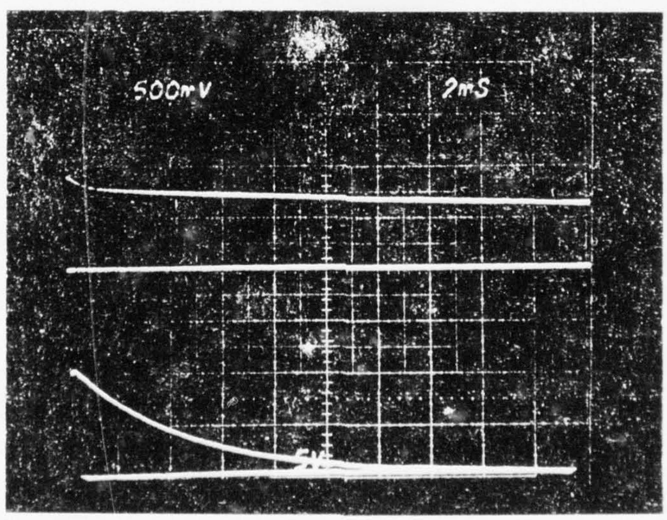

Figure 6 - Surge response of the Matsushita 8 CM MOV. Upper Trace: 500V/div. Lower trace 1 KA/div. Time scale is 2 ms/div.

The design baseline was for the ESA to survive multiple 5 ms exponential pulses with a total charge of 40 coulombs at a clamping voltage of 1 KV. In the preliminary design 8 such MOVs were used. The ballast resistors were Stackpole-made 0.5Ω disk type. The ESA package was designed to meet the requirements of compact size, prevention of arc-over, and good heat sinking.

The peak surge current of about 1 KA through each MOV implies that parisitic series resistance of greater than a few hundredths of an ohm cannot be tolerated. Many conductive epoxies and conductive ceramic frits for packaging were ruled out. The silver based electrodes of the MOVs were copper plated so that the MOVs could be welded to other components. The disk components of the ESA were stacked up together, electrically in parallel, with the electrode plates alternatively connected to two strapping electrodes. The completed ESA package weighs about 8 lbs , is 5 inches thick and has a capacitance of 0.11μF. A picture of the unit is shown in Figure 7.

The ESA was surge-tested with the pulser described above. The unit survived consecutive 40 coulomb surges. At this level the peak current was 6.5 KA at 1.1 KV. About 35 kilojoules was absorbed in the unit. The voltage and current waveforms of the test are shown in Figure 8.

From the test results one can conclude that with the present technology it is feasible to design a high energy solid state ESA using a limited number of large area MOVs at a moderate material and packaging cost. The ESA so designed can be used to replace conventional spark gaps in some applications as a primary surge protection device. Mature MOV technology capable of meeting EMP requirements will provide ESAs an order of magnitude less expensive than state-of-the-art spark gaps. However, the clamping voltage of this solid state ESA is high compared to the spark gap, which may be a drawback and should be taken into consideration in application.

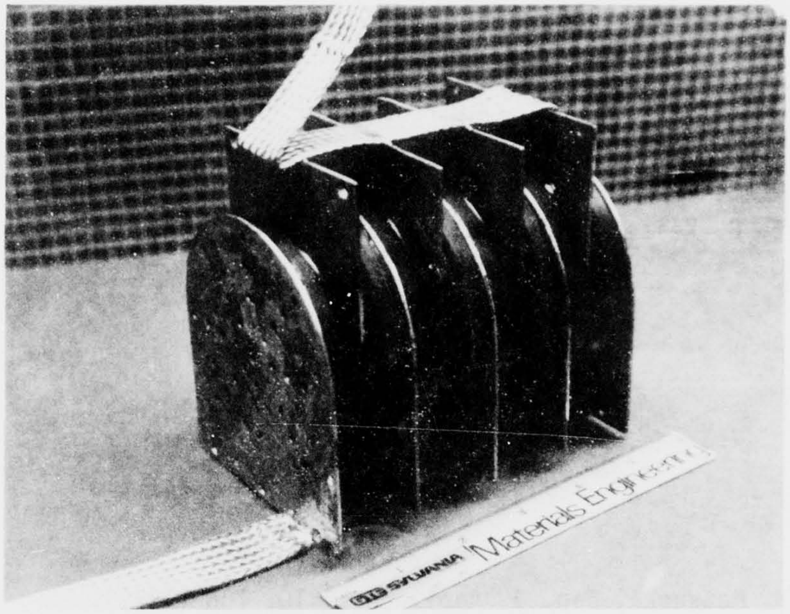

Figure 7 - The ESA consists of 8 custom made MOVs; individually ballasted with a high energy 0.5Ω resistor.

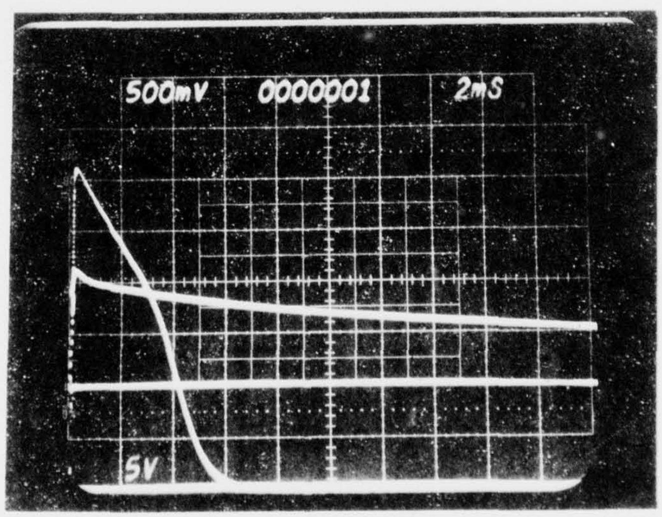

Figure 8 - The unit(shown in figure 7) was surged with the 5/200K pulser at 5.4 KV. Upper Trace: voltage across the ESA; 500V/div. Lower trace: 1 kA/div. Time scale is 2 ms/div. The current trace was distorted due to the saturation of the current probe.

Acknowledgement

The work discussed in this report was supported by GTE Sylvania under an ID program. The authors would like to thank Henning Olesen for his continued interest and encouragement. The authors are also grateful to Dan O'Leary for his technical support and to G. Keiser for his discussions.

REFERENCES

1. M. Matsuoka, Jap. J. Appl. Phys. 10, 736 (1971).

2. "Transient Voltage Suppression Manual" General Electric, 1976, Electronics Park, Syracuse, New York 13201.

3. L. M. Levinson and H. R. Phillips, J. Appl. Phys. 46, 1332, (1975).

4. J. Wong, J. Appl. Phys. 46, 1653 (1975).

5. J. Wong, P. Rao, and E. F. Koch, J. Appl. Phys. 46, 1827 (1975).

6. M. Fix and J. Sohn, Appl. Phys. Lett. 26, 519 (1975).

7. H. R. Phillip and L. M. Levinson, J. Appl. Phys. 46, 3206 (1975).

8. J. Wong, J. Appl. Phys. 47, 4971, 1976.

9. J. J. Lee, J. K. O'Brien, and M. Cooper, J. Appl. Phys, 48, March 1977.

LIGHTNING PROTECTION FOR FACILITIES HOUSING ELECTRONIC EQUIPMENT

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

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ABSTRACT

Lightning is a natural phenomenon which poses a potential hazard to people, structures, and equipment unless adequate protection is provided. The type of protection required is related to the nature and function of the facility. The decision making process involves a number of interrelated factors which should be considered when determining the need for protection.

The United States has two nationally accepted protection standards available to satisfy the needs of protection. The Lightning Protection Code is sponsored by the National Fire Protection Association (NFPA 78) and accepted by the American National Standards Institute (ANSI C5.1). The Underwriters' Laboratories sets forth the requirements for a Master Labeled System in their UL 96A. A system installed in accordance with the requirements of UL 96A can be issued a Master Label certificate. Systems conforming to either the UL or NFPA standard provide adequate protection if installed properly and if periodic inspections are performed to insure the continued integrity of the installed system.

A comprehensive survey of lightning protection systems was conducted at six FAA facilities. The surveys revealed many do's and don'ts. Some of the more obvious deficiencies along with some of the good practices are highlighted in this paper. Examples of two deficiencies found during the survey are excessive spacing between air terminals and air terminals shorter than surrounding roof-mounted objects. Other frequent deficiencies are improper bonding practices utilized to ground roof-mounted objects and roof/down conductors.

The results of the surveys emphasize that periodic inspections are necessary to reveal potential problems resulting from careless installations and the development of corrosion at connectors and fasteners.

LIGHTNING PROTECTION FOR FACILITIES
HOUSING ELECTRONIC EQUIPMENT

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1. INTRODUCTION

Lightning is an electrical discharge phenomena that occurs in the atmosphere and to the earth's surface. Lightning is both a beautiful and a terrifying sight. Unfortunately, lightning is uncontrollable, mostly unpredictable, and frequently destructive if the stroke directly hits an unprotected object. This paper explores the factors which establish the relative need for protection, reviews the principles of protection, and discusses the Master Labeled Lightning Protection System. Findings obtained during a recent series of surveys of FAA facilities are used to illustrate some of the common code violations which are made.

2. NEED OF PROTECTION

The relative need for lightning protection at a facility is dependent on many factors such as:

(a) Type or usage of facility;
(b) Personnel safety;
(c) Prevalence of lightning;
(d) Type of construction;
(e) Contents;
(f) Economic risks;
(g) Degree of isolation (relative height of surrounding structures);
(h) Type of terrain; and
(i) Height of structure.

A pragmatic type of risk analysis is suggested by the British* for aiding the decision-making process. The analysis weighs the seven factors of:

(a) Usage of structure;

(b) Type of construction;

(c) Contents;

(d) Degree of isolation;

(e) Type of terrain;

(f) Height of structure; and

(g) Relative lightning incidence.

To perform the analysis, a set of applicable conditions are listed for each of these factors. This list of conditions helps the analyzer assign the particular factor a risk index number within a range of 1 to 30 depending upon the relative criticality of the factor. Examples of types of structures and the risk index numbers which could be applied to the usage of such structures are as follows:

Type of Structure	Risk Index No.
Building housing general public	10
Facility housing electronic equipment for air traffic control	30
Private homes	2

To continue the assessment, the conditions for each of the other factors are listed, and the risk index numbers for the particular facility are assigned. The relative need for protection for the overall facility is indicated by the sum of the risk index numbers. The required sum total of the index numbers is open to selection. The British use the number 40 as their criterion; however, other sum totals may be selected depending upon circumstances.

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*"The Protection of Structures Against Lightning," British Standard Code of Practice CP 326:1965.

The decision to provide protection may be based primarily on one factor alone. Some possible single factors can be personnel safety requirements, reduced insurance rates, or to meet an imposed lightning protection code.

3. PRINCIPLES OF PROTECTION

Three basic requirements must be fulfilled to provide protection against direct lightning strikes to a structure:

(a) A conductive object must be provided to intentionally attract the leader stroke;

(b) A path must be established that joins this object to earth with such a low impedance that the discharge follows it in preference to any other; and

(c) A low resistance connection must be made with the body of the earth.

One approach to satisfying these requirements is to install an integral protection system consisting of air terminals and roof and down conductors adequately terminated to a properly configured earth electrode system. Another means of meeting these requirements is to establish a cone of protection over the facility by erecting a suitable (metal) tower or a combination of such towers with a low resistance connection to earth.

The system utilizing air terminals and roof/down conductors is used most commonly on buildings. The cone of protection method is commonly used on power transmission lines and fuel storage systems. This paper will emphasize the air terminal approach to protection.

4. LIGHTNING PROTECTION CODES

The lightning protection system should conform to an accepted set of guidelines. Codes and standards have been established in many countries to provide the necessary guidelines. Every code or requirement has one thing in common and that is diverting a direct strike to earth. The primary difference in the various codes is the philosophy used in achieving an effective protection system.

The United States has two nationally accepted codes: the National Fire Protection Association's Lightning Protection Code (ANSI C5.1), and the Underwriters' Laboratories Master Labeled Lightning Protection System (Standard UL 96A). The requirements of these two codes are quite similar and are probably equally utilized on structures throughout the nation. The major difference between the two is that the Master Label can be certified upon both a factory inspection and labeling of the lightning protection materials and upon performance of a field inspection by an authorized inspector.

5. PROCEDURE FOR ACQUIRING A MASTER LABEL

Assume that it has been determined that a lightning protection system is required on a new or existing facility. The procurement specification should indicate whether the system is to be a certified Master Labeled System in accordance with the UL 96A or a non-certified system installed in accordance with the NFPA-78 or UL 96A.

Let's assume the specification requires that a certified Master Labeled System will be installed. The first step in acquiring a certified system is to design the system using the guidelines set forth in the UL 96A. This design may be done in-house or by an architectural engineering firm. Then, construction of the system is contracted out and the contractor assumes the responsibility for supplying the certified system.

Another means of acquiring the Master Label is to contract for both design and construction through a UL-approved manufacturer of lightning protection equipment. Often this route is the easiest means of getting a certified system.

Upon completion of the installation and the field inspection, the application is signed by the owner and contractor and forwarded to the Underwriters' Laboratories. Underwriters' Laboratories then returns a 2-1/2" x 4" brass Master Label for attachment to the facility.

The procurement of a lightning protection system installed in accordance with the NFPA-78 involves a procedure that is basically the same as that for a certified system. However, closer supervision will be necessary to insure that the system is installed as required by the Code.

The installation of the lightning protection system does not mean that it can be ignored forever. Periodic inspections should be performed. Over a period of time, air terminals can be damaged by direct strikes, and corrosion on connectors and at joints may increase the lightning path resistance. Also, the inspection can reveal unprotected areas or where additions to the structure have not been properly protected.

6. COMMON LIGHTNING PROTECTION SYSTEM DEFICIENCIES

The overall requirements of either UL 96A or NFPA-78 are too lengthy to expand upon in this paper. Therefore, just the most commonly abused practices observed during recent surveys are illustrated.

Many FAA facilities, particularly Air Route Traffic Control Centers (ARTCC), do have comprehensive lightning protection systems installed. However, as time has passed and structural changes have been made, the lightning protection system has not always been updated to insure that it continues to provide its original degree of protection. Figures 1 to 7 illustrate some areas where proper attention has not been paid to the detailed requirements of the codes.

6.1 Air Terminal Location and Height

Air terminal location and height relative to objects to be protected are two important factors which are commonly overlooked. Paragraphs 22 and 30 of the UL 96A require that:

> "Air terminals shall extend above the object to be protected not less than 10 inches or more than 36 inches . . ."

> "Metal cupolas, ventilators, finials, spires, flag poles, radio staffs, television and FM antennas, chimney extensions and caps, or other permanent metal elevations shall be bonded to the main lightning conductor. Air terminals shall be optional on such metal elevations if the metal is of sufficient strength and conductivity to approximate that of a standard air terminal . . ."

Two examples of the above deficiencies are shown in Figures 1 and 2. Note that metallic objects such as antennas, antenna masts, air vents, exhaust vents, guardrails, etc. extend higher than the air terminals. The lightning

Figure 1. Security Light Extends 3 Feet Above Air Terminal.

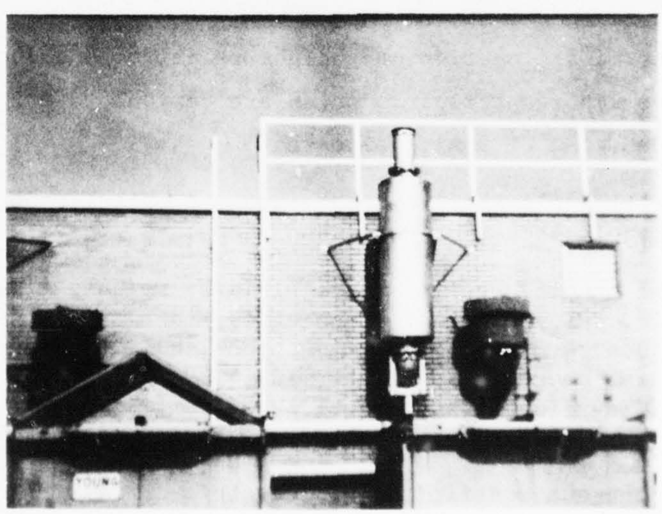


Figure 2. No Air Terminals on Guardrails.

system serves no function in these areas since an impending lightning stroke would strike one of the higher objects instead of the air terminal.

6.2 Air Terminal Spacing

Inadequate spacing of air terminals is another frequently encountered deficiency. Air terminals should be such that the incoming stroke will have a higher probability of striking the terminal rather than the structure. The requirements of UL 96A are that:

> "Air terminals shall be placed on ridges of gable, gambrel, and hip roofs, around the perimeter of flat roofs, and on the corners and edges of gently sloping roofs at intervals not exceeding 20 feet, except that air terminals 24 inches or higher may be placed at intervals not exceeding 25 feet."

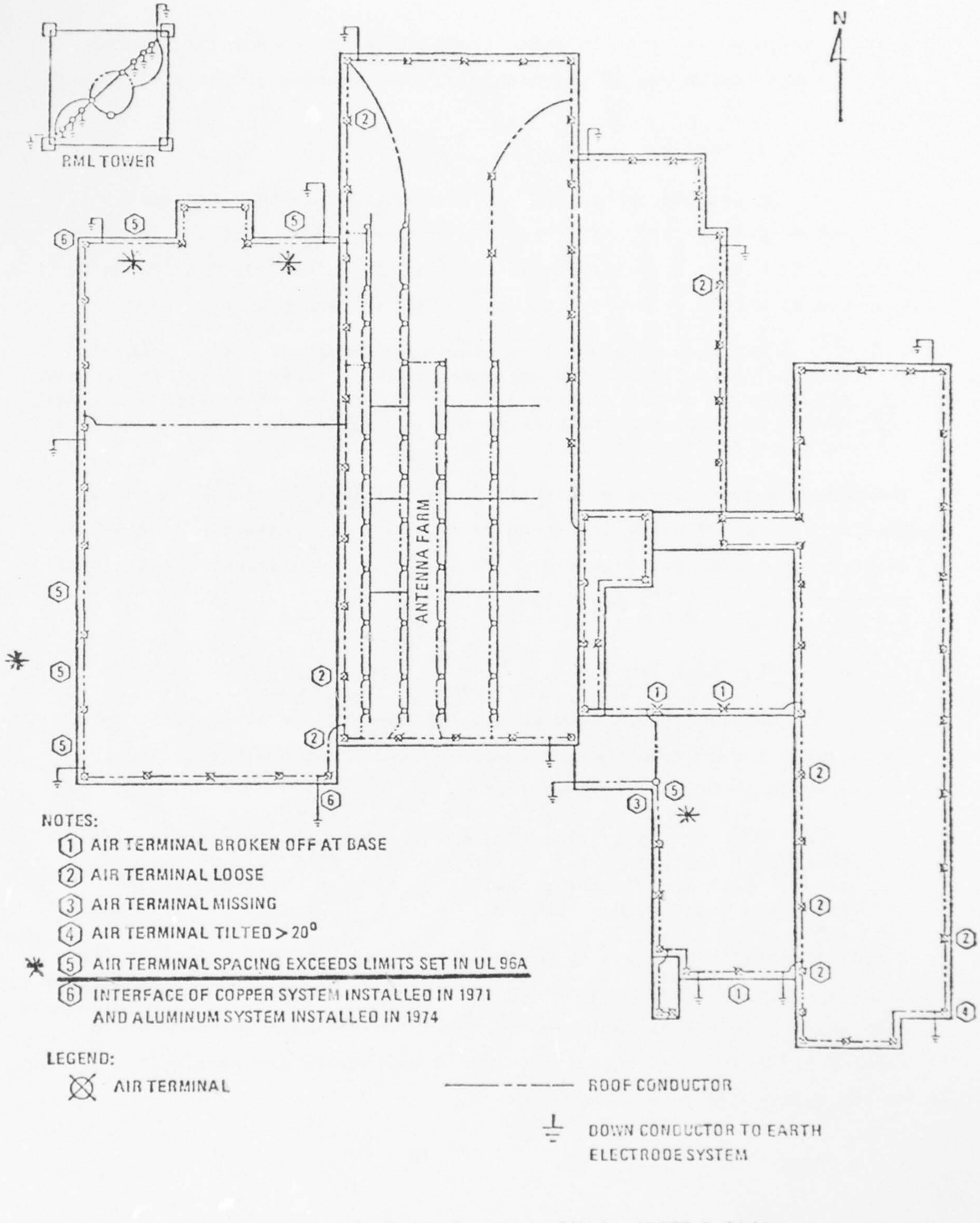
The recent surveys revealed air terminals spacings ranging from 16 to 26 feet with 1 out of every 16 exceeding the 20-foot separation distance for 24 inch terminals (see Figure 3). To meet code requirements, additional air terminals should be installed.

6.3 Flat Roof Coverage

Complete protection should be provided for large flat roofs. This protection is sometimes neglected on roofs which are very wide. Paragraph 26 of UL 96A requires that:

> "Flat or gently sloping roofs which exceed 50 feet in width shall have additional air terminals on the flat or gently sloping areas. Such air terminals shall be placed on the conductor at intervals not exceeding 50 feet."

A typical example of where this requirement has been overlooked is the Atlanta ARTCC building, also shown in Figure 3. A major portion of the main ARTCC building is approximately 80 feet wide with no interior air terminals. Flat roofs this large should have extra air terminals installed in the manner illustrated by Figure 4.



As Built Drawing of Main ARTCC Building
Lightning Protection System

Figure 3. Air Terminals on Main ARTCC Building at Atlanta.

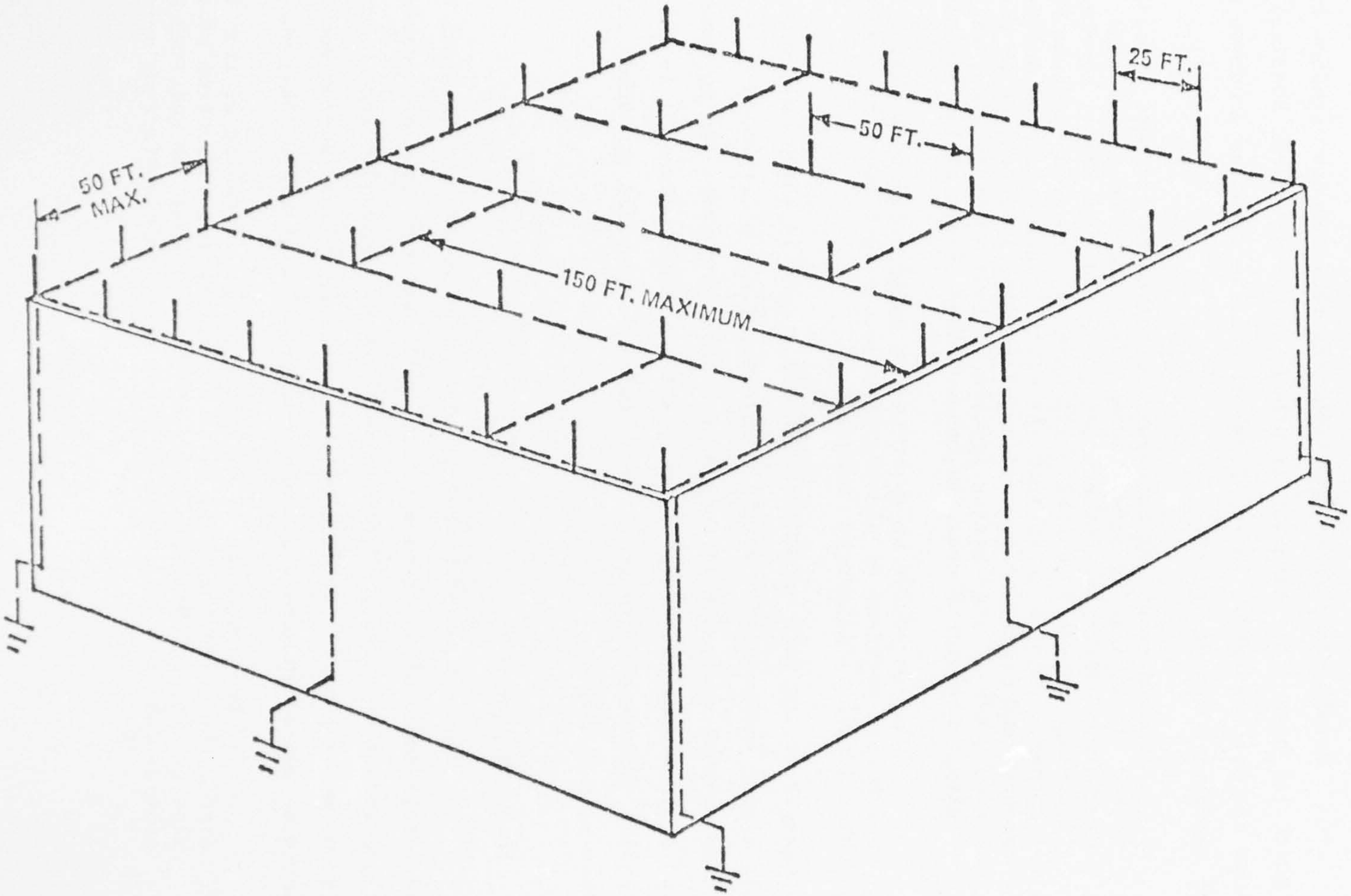


Figure 4. Air Terminal Placement on Flat-Roofed Structures.

6.4 Common Grounding

Metal objects near the lightning roof and down conductors pose a potential hazard of flashover if proper grounding (cross bonding) practices are not observed. In Paragraph 81, UL 96A requires a common ground for the entire system, to wit:

> "Common grounding has been recognized as the most effective method of eliminating side flashes resulting from a lightning discharge. Therefore, structures protected by a Master Labeled lightning protection system shall have all grounding mediums bonded together. This is to include all electric and telephone service grounds and other underground metallic piping systems which enter the structure. Such piping systems include water service, gas piping, underground conduits, underground LP-gas piping systems, etc."
>
> "Caution should be exercised to avoid bonding to piping systems which have sections of plastic pipe unless such sections are bridged by a length of main-size conductor."

An example of the lack of a direct common ground is shown in Figure 5. This figure shows several metallic objects, i.e., power conduit, fences, and an exhaust vent, within inches of a down conductor, yet no common bond is provided. However, Figure 6 shows another situation in which all metallic objects are properly cross bonded to the down conductor in accordance with UL 96A.

6.5 Guards

Down conductor guards are installed to prevent physical damage and displacement of the conductor. Guards should be made of nonmetallic or nonferrous materials. Unfortunately, it is common practice to use ferrous metal guards. If iron or steel conduit is used as the guard, it should be bonded in accordance with Paragraph 54 of the UL 96A, which says:

> "If the conductor is run through pipe or tubing of iron or steel, the conductor shall be bonded to the top and bottom of the pipe or tubing. Only one bond (at the top) shall be required if the pipe or tubing is of copper or other acceptable nonferrous metal."

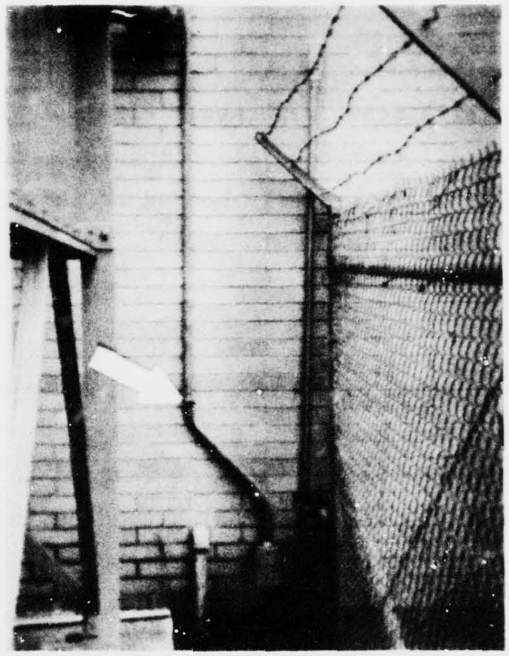


Figure 5. Lack of Cross Bonding Between Down Conductor and Adjacent Conductors.

Figure 6. Down Conductor Cross Bonded to Nearby Metallic Objects.

Numerous ferrous down conductor guards were found to be open at one or both ends at the installations inspected. Figure 7 illustrates an improperly bonded guard. Such conditions should be corrected to insure that both ends of guards are properly bonded to the lightning down conductor.

7. SUMMARY

Lightning is a natural phenomenon which poses a potential hazard to people, structures, and equipment unless adequate protection is provided. The type of protection required is related to the nature and function of the facility. The decision making process involves a number of interrelated factors which should be considered when determining the need for protection.

The United States has two nationally accepted protection standards available to satisfy the needs of protection. Systems conforming to either the UL or NFPA standard provide adequate protection if installed properly and if periodic inspections are performed to insure the continued integrity of the installed system.

A comprehensive survey of lightning protection systems was conducted at six FAA facilities. The surveys revealed many do's and don'ts. Some of the more obvious deficiencies along with some of the good practices are highlighted in this paper. The results of the surveys emphasize that periodic inspections are necessary to reveal the existence of deficiencies.

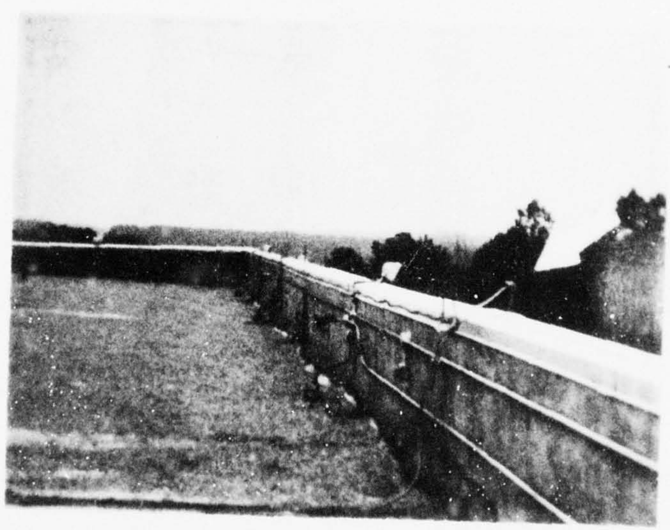


Figure 7, Improper Grounding of Ferrous Down Conductor Guard.

GROUNDING REQUIREMENTS FOR

PROTECTION OF TRANSPORTABLE SATELLITE COMMUNICATION TERMINALS

(GROUNDING REQUIREMENTS FOR ELECTROMAGNETIC PULSE (EMP) AND LIGHTNING PROTECTION OF TRANSPORTABLE SATELLITE COMMUNICATIONS TERMINALS)

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

This paper indicates how existing theoretical and experimental knowledge concerning grounding requirements for the protection of structures in general can be implemented for the special case of the transportable SATCOM terminal.

The paper begins with a description of a typical SATCOM terminal and gives terminal specifications in detail (Sections 2.0 and 3.0). Section 4.0 discusses "Protection Requirements". General protection requirements are that transportable SATCOM terminals must meet performance requirements, must not be damaged by direct lightning strokes, must not be degraded beyond allowable tolerances due to the effect of an electromagnetic pulse (EMP), and must be safe for personnel work.

More specifically, under the heading "Performance Requirements," an adequate grounding system is described, including a description of site ground fields. "Lightning Protection" for antenna structures, equipment shelters, combined protection, power modules and the role of electrical surge arrestors is covered intensively, as is "EMP Protection" for antenna structures, equipment shelters and power modules, electrical surge arrestors, cable shields and connectors, and cable routing. Examples of grounding systems for two configurations of transportable SATCOM terminals are compared under the heading "Typical Installations" (5.0).

In summary (6.0), the paper concludes that the same principles which protect power lines, radio and t.v. transmission towers, houses, etc., from the effects of lightning need to be adapted and incorporated to the greatest extent possible to protect transportable SATCOM terminals. With additional adaptions these same principles also provide protection against the effects of EMP. The crucial protection in both cases is grounding.

1.0 INTRODUCTION

Transportable satellite communication terminals, simply because of their transportability, encounter a number of grounding problems. They require protection systems that are able to function properly in extremely different environments as unlike as Arctic tundra and African desert, beachfronts and mountain tops. If the van-mounted equipment and antenna structures are situated atop a mountain or are the highest objects in an area, for instance, they become more susceptible to lightning and electromagnetic pulse problems than at lower levels. Site soil conditions, ranging from granite to quicksand, pose additional problems. Unfavorable site resistivities can make grounding or "earthing" of terminals a most formidable task.

This paper will indicate how existing theoretical and experimental knowledge concerning the protection of various types of structures can be implemented for the special case of transportable SATCOM Terminals.

2.0 TYPICAL SATCOM TERMINALS

A basic SATCOM Terminal consists of an equipment shelter (or van) which houses the various types of electronic equipment (transmitters, receivers, modems, processors, environmental control equipment, etc.); an antenna structure of one type or another; a power module (if the terminal has no access to local utility power mains); a site ground field; and the associated cabling required for communication, status indication, and control between all component subsystems. Such a system is shown in Figure 1.

A somewhat more complex system is illustrated in Figure 2. Here an electronics module at a remote site may communicate with a control site over a line-of-sight microwave link of many miles, perhaps 50 to 100 miles, with environmental conditions extremely different

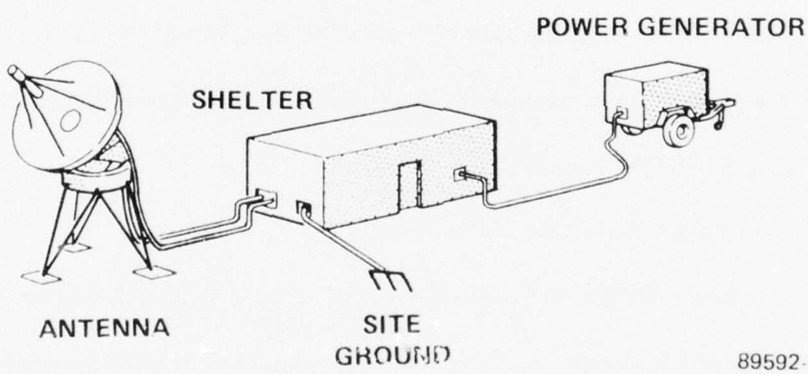

Figure 1. Basic Transportable SATCOM Terminal

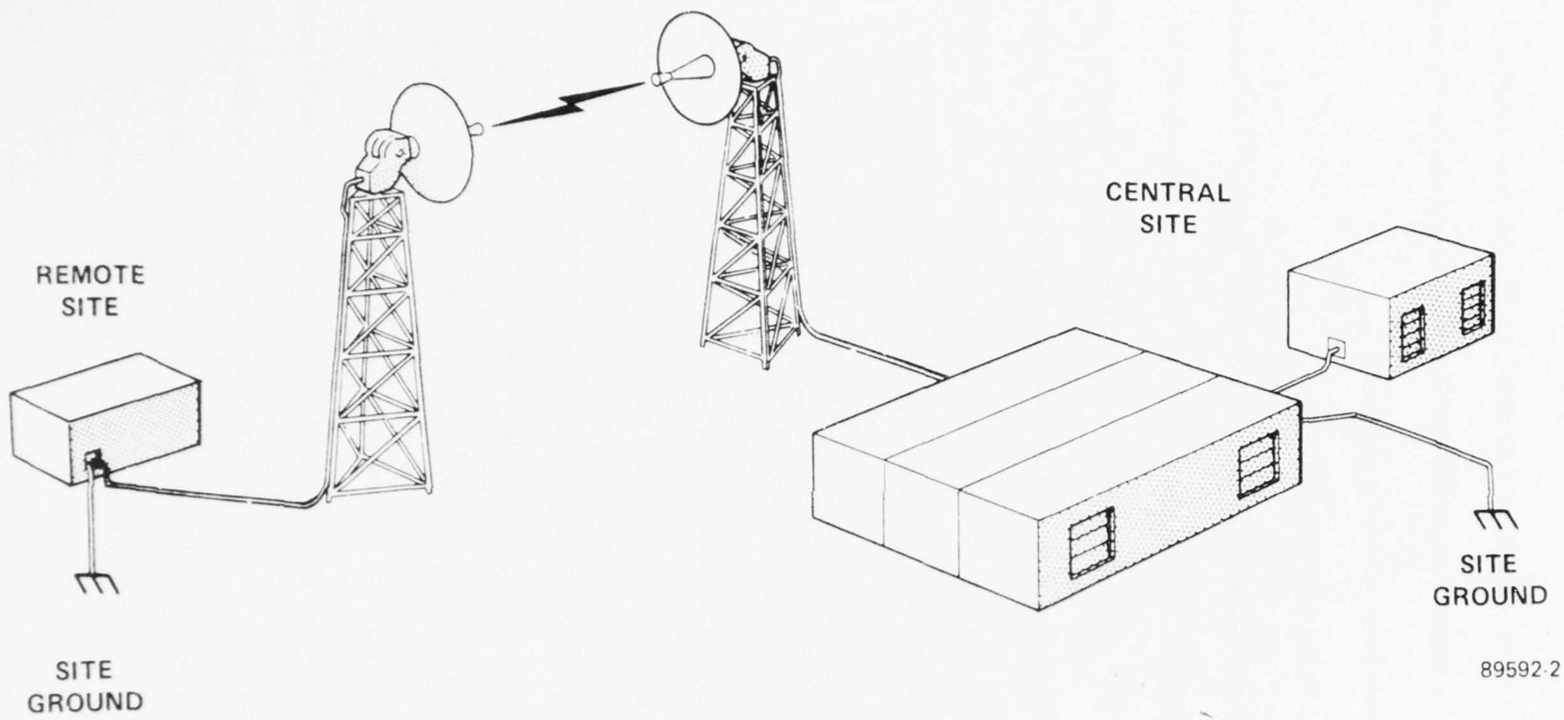

Figure 2. Typical Microwave Link Between Remote and Central Sites

at each site. For example, the remote site terminal could have been located on a snow covered rock-based mountain ridge while the central site is settled in a moist fertile valley plain. (The power generators have been purposely omitted.)

3.0 SPECIFICATION REQUIREMENTS

Today, transportable SATCOM terminals are required to withstand, without damage, the effects of direct lightning strokes. More and more they are being required to withstand the effects of exo-atmospheric nuclear detonations, which are the source of EMP. And, as always, an adequate grounding system must be provided to assure that the installation will meet its performance requirements. Military specifications such as MIL-STD-1541,[1] MIL-STD-1542,[2] and MIL-B-5087 (ASG),[3] which specify bonding, grounding, shielding, filtering, and lightning protection procedures are being imposed. Military specifications such as MIL-STD-461A,[4] MIL-STD-462,[5] and MIL-E-6051D,[6] which specify radiated and conducted emissions and susceptibility limits, test procedures, and electromagnetic compatability margins are being imposed. For terminals to be located in Western Europe, various CISPR (Comite International Special des Perturbations Radioelectriques - International Special Committee on Radio Interference) regulations concerning interference control and safety procedures apply. One of the most familiar foreign specifications being applied to U.S.-made equipment is VDE 0875.[7] VDE is the abbreviation for Verband Deutscher Elektrotechniker, an association of West German engineers, comparable to our own Institute of Electrical and Electronic Engineers (IEEE), combined with the Underwriters Laboratories (UL) who have an effect on West German legislation. VDE participates in CISPR, and many requirements are common. Last but by no means least, more systems are being required to be designed in accordance with the Defense

Nuclear Agency (DNA) Handbooks - DNA 2113H-1,[8] DNA 2113H-2,[9] and DNA 2113H-3,[10] - which give guidance for protection against the effects of EMP.

It would seem at first glance that it might be impossible to satisfy all of the above requirements at the same time; to be sure, compromises must at times be made to assure that mission critical performance is given its proper priority along with the safety of personnel and equipment.

4.0 PROTECTION REQUIREMENTS

From a simplistic standpoint, the four basic requirements imposed upon a transportable SATCOM terminal are that:

- It must meet its performance requirements.
- It must not be damaged by direct lightning strokes.
- Its specified performance parameters must not be degraded beyond allowable tolerances due to the effects of EMP.
- It must be safe for personnel to work, in, on, or about, regardless of natural or man-made environmental conditions.

A. Performance Requirements

Suffice it to say that some minimum grounding system is required to assure that the system will meet its requirements relative to performance specifications and that a suitable one, including a site ground field, has been determined, designed, and installed. This may be a single-point ground system (also called "crows-foot" or "Christmas-tree" ground systems) or a multipoint ground system (either purposely, inadvertently, or through careful compromise). It may require anywhere from a 1-, 5-, or 10-ohm D. C. ground resistance to earth to no purposeful ground connection. The techniques for assuring an adequate system ground for performance

purposes lie essentially in providing adequate gauge copper grounding conductors, interfaced at busses or common points in a manner which minimizes the inherent added resistance of any connection; in providing suitable protection against corrosion and galvanic action through the careful choice of materials and plating; and in providing the design of the site "earthing" field, after taking into consideration the characteristics of the soil conditions at that particular location.

B. Lightning Protection

The fundamental characteristic of a lightning protection system for a SATCOM Terminal is that it be devised so that the current produced by a direct stroke may enter or leave the earth without passing through either a nonconducting part of the terminal elements or through a conducting portion of the elements which would be unable to pass the current without suffering damage or catastrophic destruction. As previously illustrated in Figures 1 and 2, representative SATCOM terminals consist of an antenna structure, an electronics equipment shelter (or van), and in many instances (although not all), a power module consisting of some type of internal combustion engine-generator set, or battery-inverter set, or both. Since the antenna structure portion of any terminal is usually the highest of the three basic elements, there is a very high probability of it becoming part of the lightning current path. The other units, being somewhat lower usually, are not as apt to be struck; however, in many cases it is desirable to provide them with protection "just in case." I am sure all of you are aware of the fact that lightning is very strange phenomenon and that there are many recorded instances where it didn't "behave as it was supposed to."

1. Antenna Structures

The antenna itself and the structures which support it must have adequate protection to prevent lightning strokes from causing damage to the antenna,

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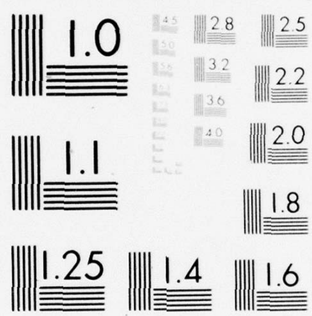

MICROCOPY RESOLUTION TEST CHART
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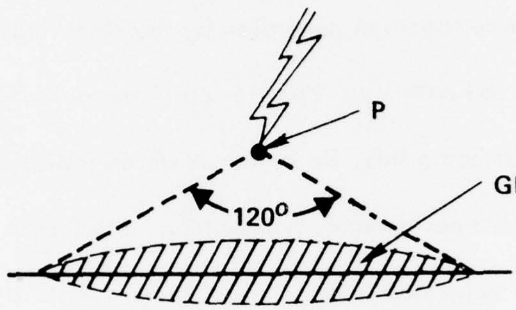
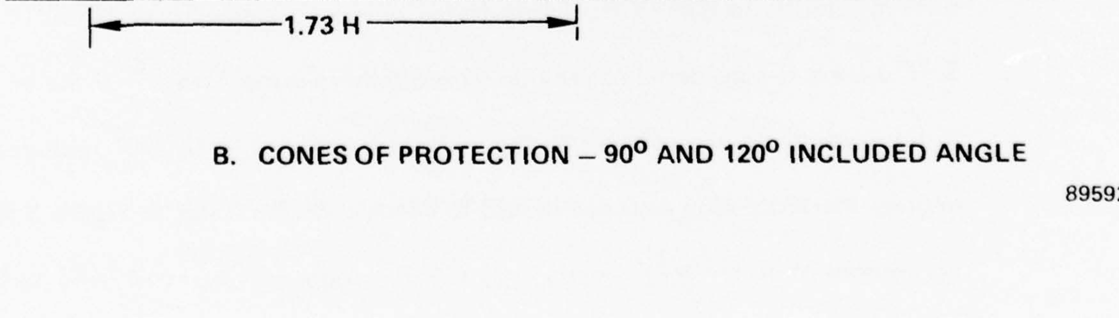
the transmission lines, and associated equipment located both on the antenn structure as well as in the equipment van. To provide an antenna with protection and to ensure that the strike will travel to ground by a predetermine route, it is necessary to provide a path which has a very low impedance ov the frequency spectrum generated by the lightning impulse. Essentially, th predetermined path must "short circuit" the antenna and its supporting struc One way of doing this, for antennas whose radiation pattern is not degrade past specified performance parameters, is to install an air terminal (lightnir rod) to the uppermost edge of the antenna. This air terminal must be long enough so that an adequate "cone of protection" is provided to enclose the antenna itself and all structural elements.

Figure 3(A) illustrates the cone of protection provided by a single conduct point, P, suitably grounded. This figure is identical to Figure 7-A of MIL-5087B (ASG).[11] It may be noted that this cone consists of the space under apex of an imaginary cone whose included angle is 120° when rotated abou vertical line between the point, P, and the earth. The angle of the conic surface relative to that vertical line is, of course, 1/2 of 120° or 60°.[12] Such a cone is considered to provide 99% effective protection.[13] If the a of the conical surface relative to the vertical is reduced to 45° (90° includ angle), the protection afforded is said to become 99.9% (refer to Figure 3 For reasons of cost-effectiveness, only the 60° angle will be considered he Figure 4 illustrates a very basic antenna structure indicating how the air



A. CONE OF PROTECTION – 120° INCLUDED ANGLE



B. CONES OF PROTECTION – 90° AND 120° INCLUDED ANGLE

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Figure 3. Lightning Protective Zones Created by a Single Conductive Point P, Suitably Grounded

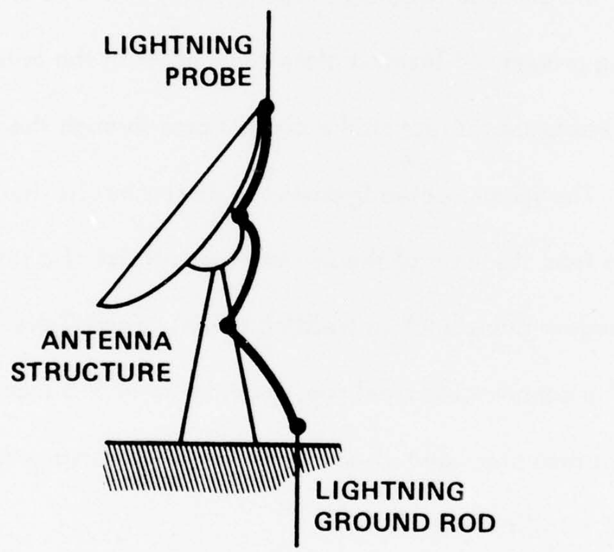

Figure 4. Lightning Protection of a Basic Antenna Structure

terminal is attached to the upper edge of the reflector. It is very important to note that the air terminal base or holder must be bonded electrically to the antenna itself to avoid "flashover" due to differences in potential during a strike.

Also noteworthy in the figure is the connection between the base of the air terminal and some common point on the structure supporting the reflector, which in turn traverses the elevation bearing and is connected to the lower portion of the antenna structure, from which point a connection is made to a lightning ground rod located close to or beneath the antenna structure. It is not desirable that direct stroke current pass through the elevation gears or bearings. The jumper cable bypasses or short-circuits that path. All down-conductors from the base of the air terminal consist of a suitably-sized stranded copper cable such as welding cable. Each lightning ground rod consists of a copper-clad steel rod, a minimum of 5/8 inch but preferably 3/4 inch in diameter, and of adequate length (consisting of two sections for ease of installation).

A simple protection system as described above is suitable for antennas which are fixed in azimuth, or which have their azimuth adjusted by either physically realigning the antenna on the site, or for truck roof-mounted antennas which may have their antenna base (the truck) "aimed" in a different direction.

For the case where azimuth adjustability is designed into the antenna structure, provision must be made to bypass the azimuth gears and bearings also. This is

done by routing a suitably sized copper conductor down into the cable wrap area where it will encircle the axis of azimuth rotation the required amount to allow for unimpeded antenna rotation. It then exits the cable-wrap area and is routed to a lightning ground rod beneath the antenna. All component metallic members of which the antenna structure is comprised should be electrically continuous to the common bonding points on the upper and lower antenna structures to prevent flashover during a direct stroke.

2. Equipment Shelters

Most equipment shelters utilizing the SATCOM Systems consist of metallic outer skins, and there is at least one ground stud connecting the metallic shelter back to the System Ground Point (SGP). To protect against the possibility of a direct lightning stroke to the shelter with uncontrolled current paths to earth, air terminals are usually attached to the shelter in such a way that those currents are routed directly to earth.

Figure 5A illustrates an equipment shelter which is protected by one lightning rod. The assumption here is that the air terminal is high enough to fully enclose the entire shelter within the required 60° "cone of protection." Figure 5B illustrates the use of two air terminals to protect either a larger shelter or the use of two shorter probes rather than one long one. In this case, for more efficient coverage, each probe would be on a corner diagonally opposite to the other.

It should be noted that the air terminals may be mounted at <u>any</u> convenient location atop the shelter which provides the overlapping cones of protection,

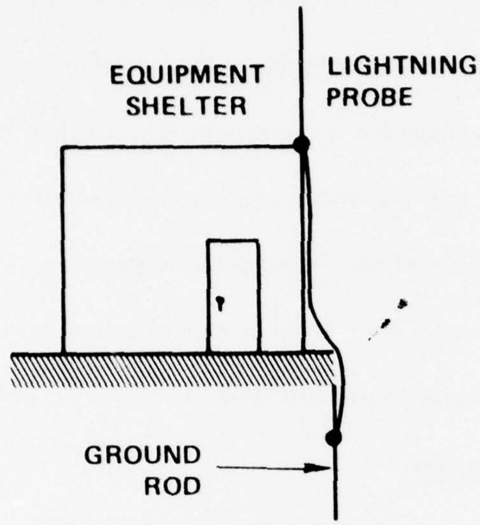

Figure 5A. Equipment Shelter Protected by One Air Terminal

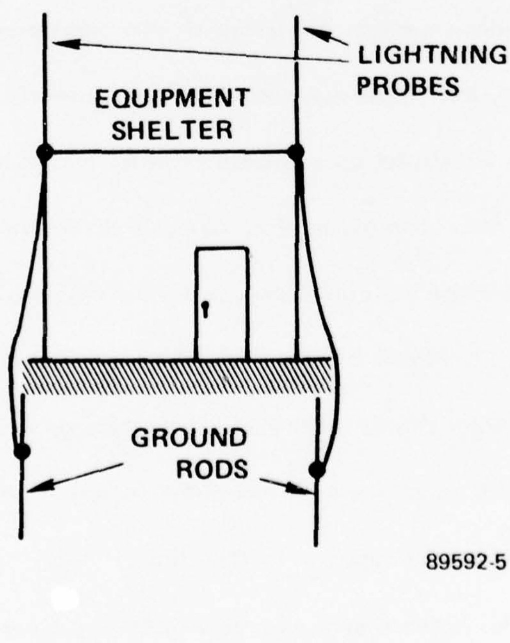

Figure 5B. Equipment Shelter Protected by Two Air Terminals

as long as each air terminal has its own down-conductor and ground rod located directly beneath. The minimum bend radius in the down-conductor must be 8 inches, and the maximum angle formed by the conductor should not be greater than 90°. The air terminal or the down-conductor must be connected to the metallic skin of the shelter at the highest convenient point on the shelter to prevent flashover. In some instances, the shelter skin itself may be utilized as part of the down-conductor system, or it may be used as a redundant or "backup" part of it.

Figure 6 illustrates the use of multiple air terminals and grounding rods to protect a complex of two abutted equipment shelters. Also to be noted are the height of the air terminals required to provide the cones of protection and the fact that the shelter metallic skin is used as part of the down-conductor system.

Figure 7 illustrates a possible connection of an air terminal at the top of a welded corner-seam shelter, and Figure 8 is a representative connection of the down-counter near the bottom of the shelter. The air terminal adaptor and the down-conductor flange must be either welded to the shelter skin or provided with electrically-conductive surfaces suitably-plated or otherwise protected against corrosion.

3. Combined Protection

Figure 9 illustrates how a single air terminal may be used to protect both the antenna and the equipment shelter (or vehicle) which supports it. Figure 10A shows a phased array antenna mounted atop its associated electronics

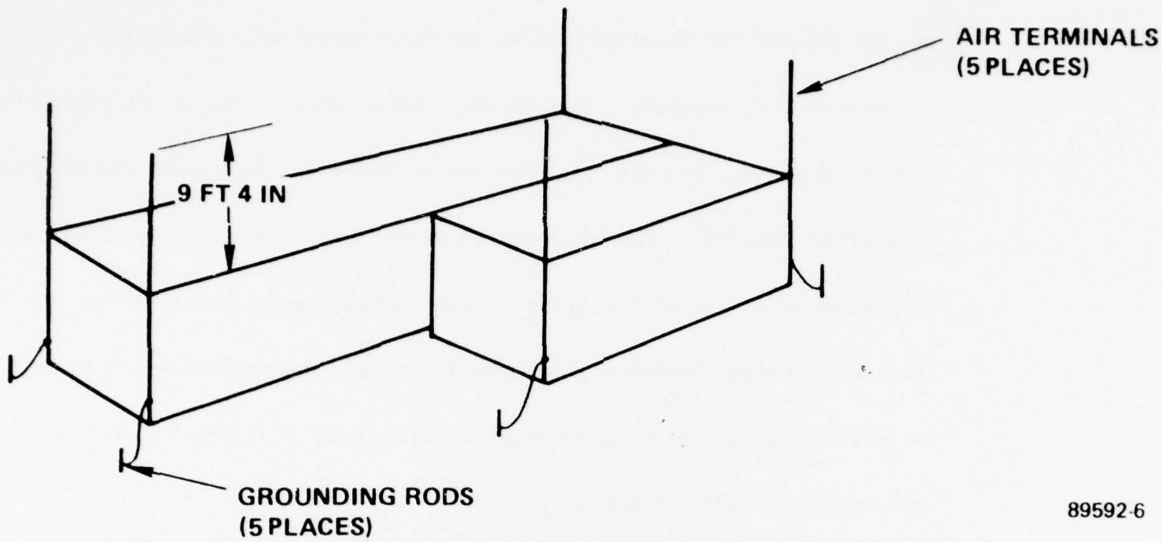

Figure 6. Equipment Shelter Complex Protected by Multiple Air Terminals

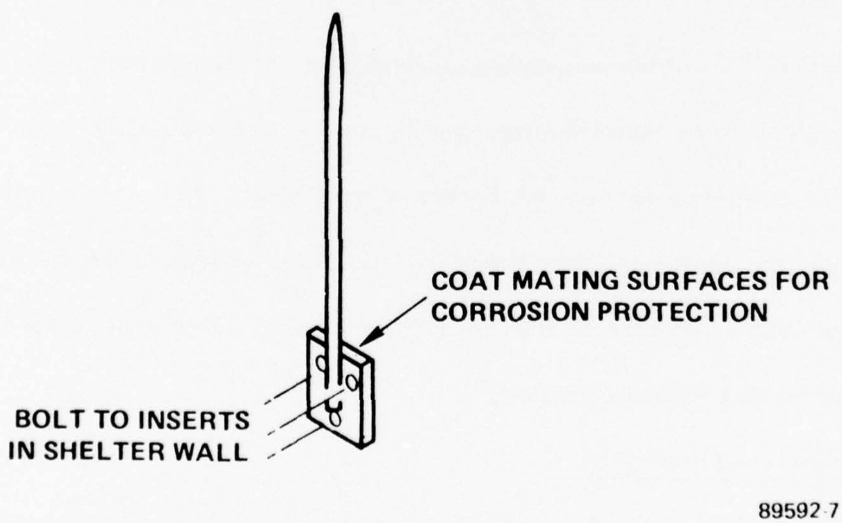

Figure 7. Possible Connection of Air Terminal at Top of Welded Seam Shelter

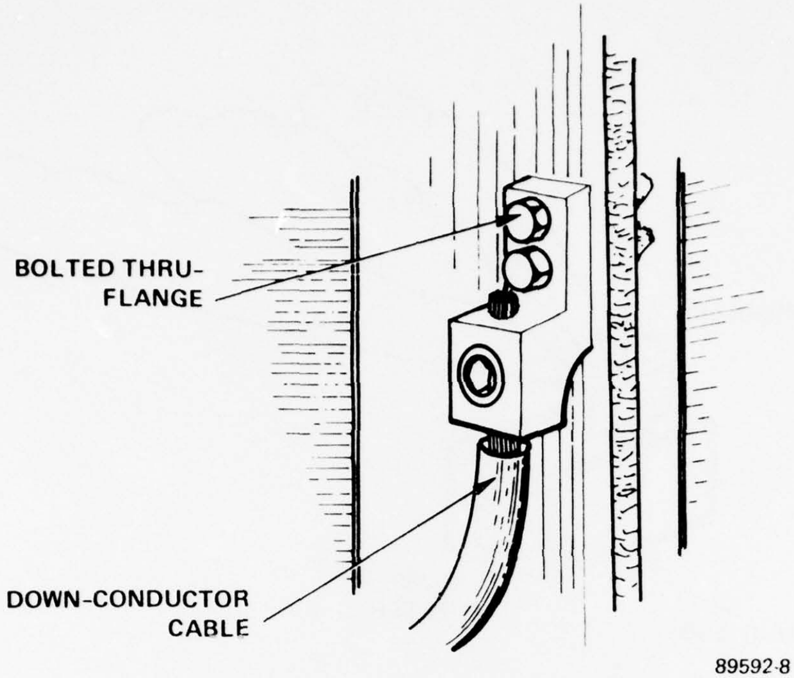

Figure 8. Connection of Down-Conductor Near Bottom of Welded Seam Shelter

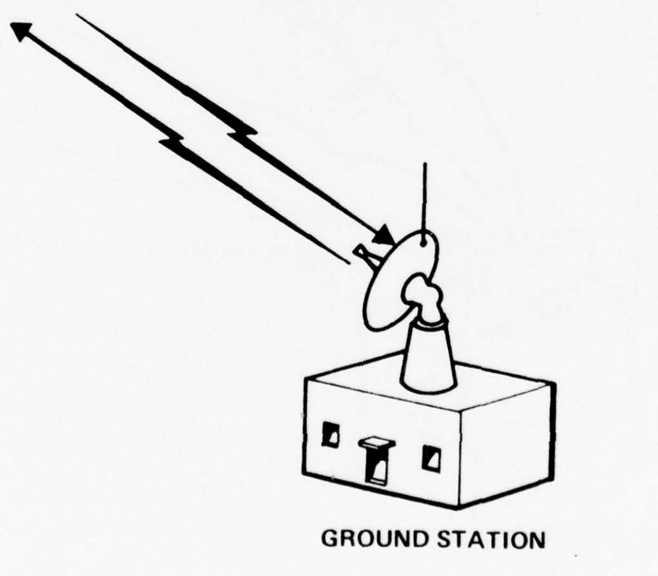

Figure 9. Air Terminal Providing Protection to Both Antenna and Shelter

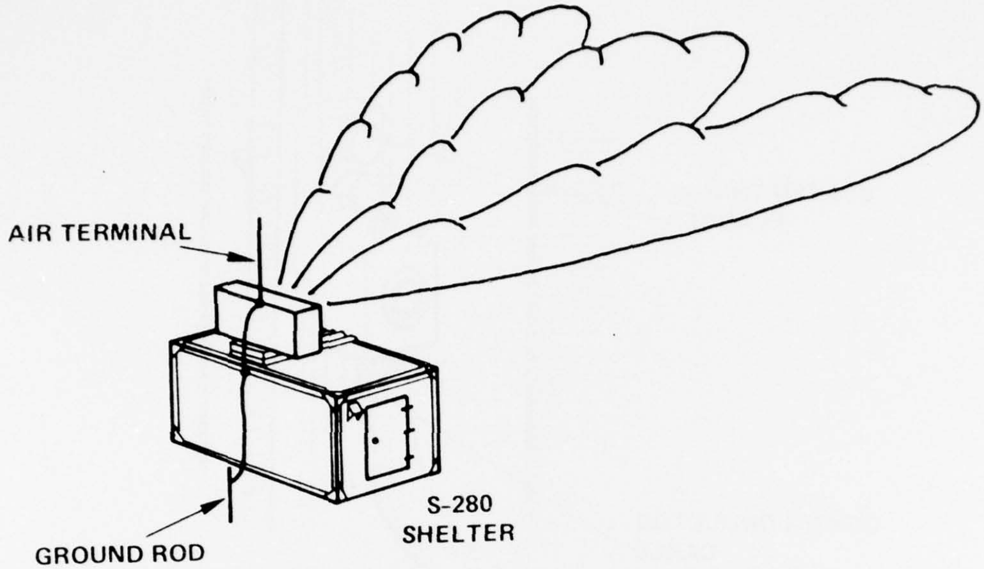

Figure 10A. Single Air Terminal Mounted on Antenna to Protect Both Antenna and Shelter

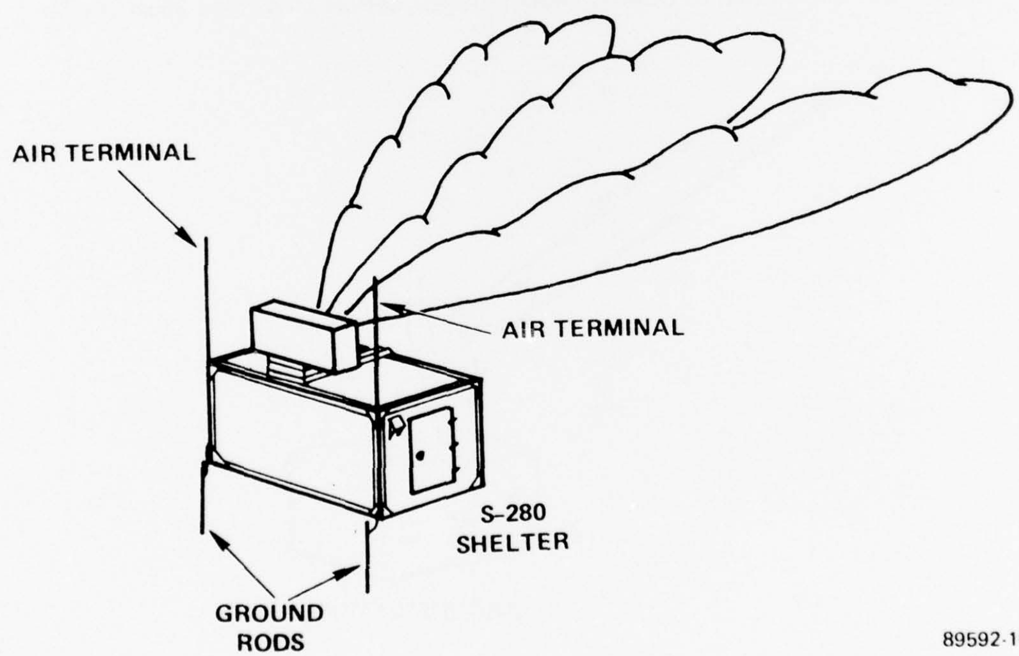

Figure 10B. Air Terminals Mounted on Shelter to Protect Antenna and Shelter

equipment shelter. Assuming that the air terminal would not affect the radiation patterns of the "steered" beam, then the use of one such terminal could be used to protect both the array and the shelter. If for some reason it was more desirable to install the lightning protection on the shelter rather than the antenna then a scheme such as indicated in Figure 10B could be implemented. In both cases it is assumed that the array structure is fixed as shown and only the beams are adjustable in azimuth. It goes without saying that the air terminals would have an effect on the radiation pattern if they are directly in the path of the beam.

Figure 11 is an artists conception of an actual tower (admittedly not transportable) upon which is mounted a multitude of antennas and which contains associated equipment shelters and other ancillary gear within. The manner in which this particular tower is protected against lightning is illustrated in Figure 12. It should be noted that if the radome or canopy which covers the antenna atop the tower were not supported by conducting tubing, but rather was entirely non-conductive, then discrete down-conductors would be required between the air terminal around the canopy to the main down-conductors. And if the air terminal were not high enough, there would be a danger zone within the canopy as illustrated in Figure 8B of MIL-B-5087 (ASG)[14] as reproduced here in Figure 13. The point to be made here is that there is always some height of the air terminal associated with the proper protection of any structure. The reason for including a discussion of a non-

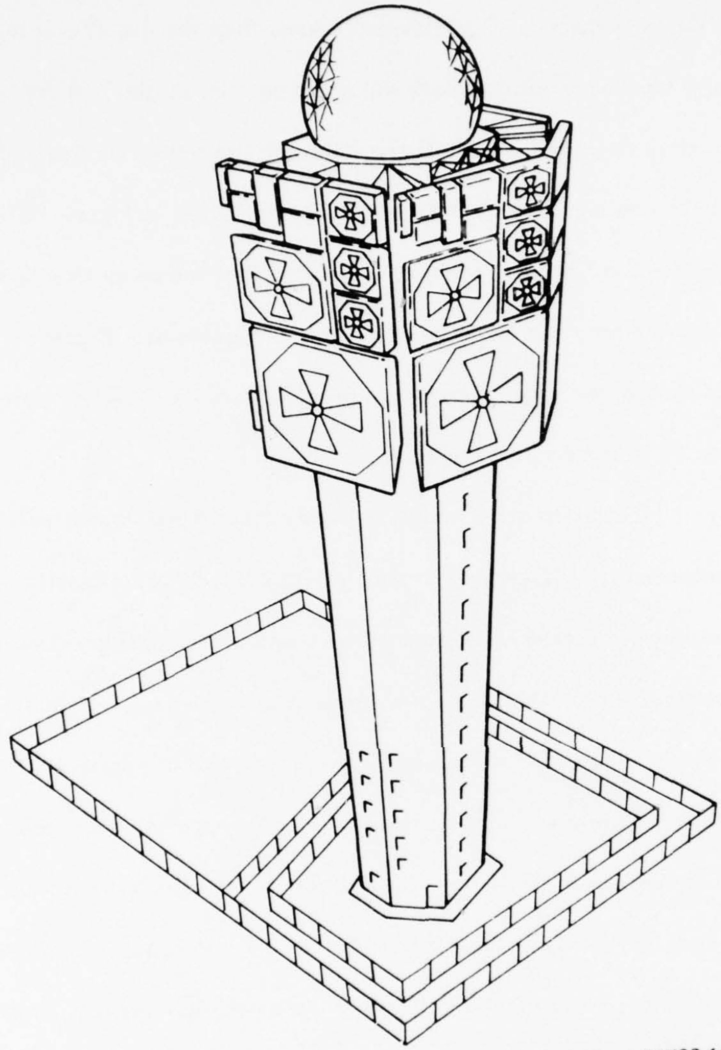

Figure 11. Tower-Mounted Antennas

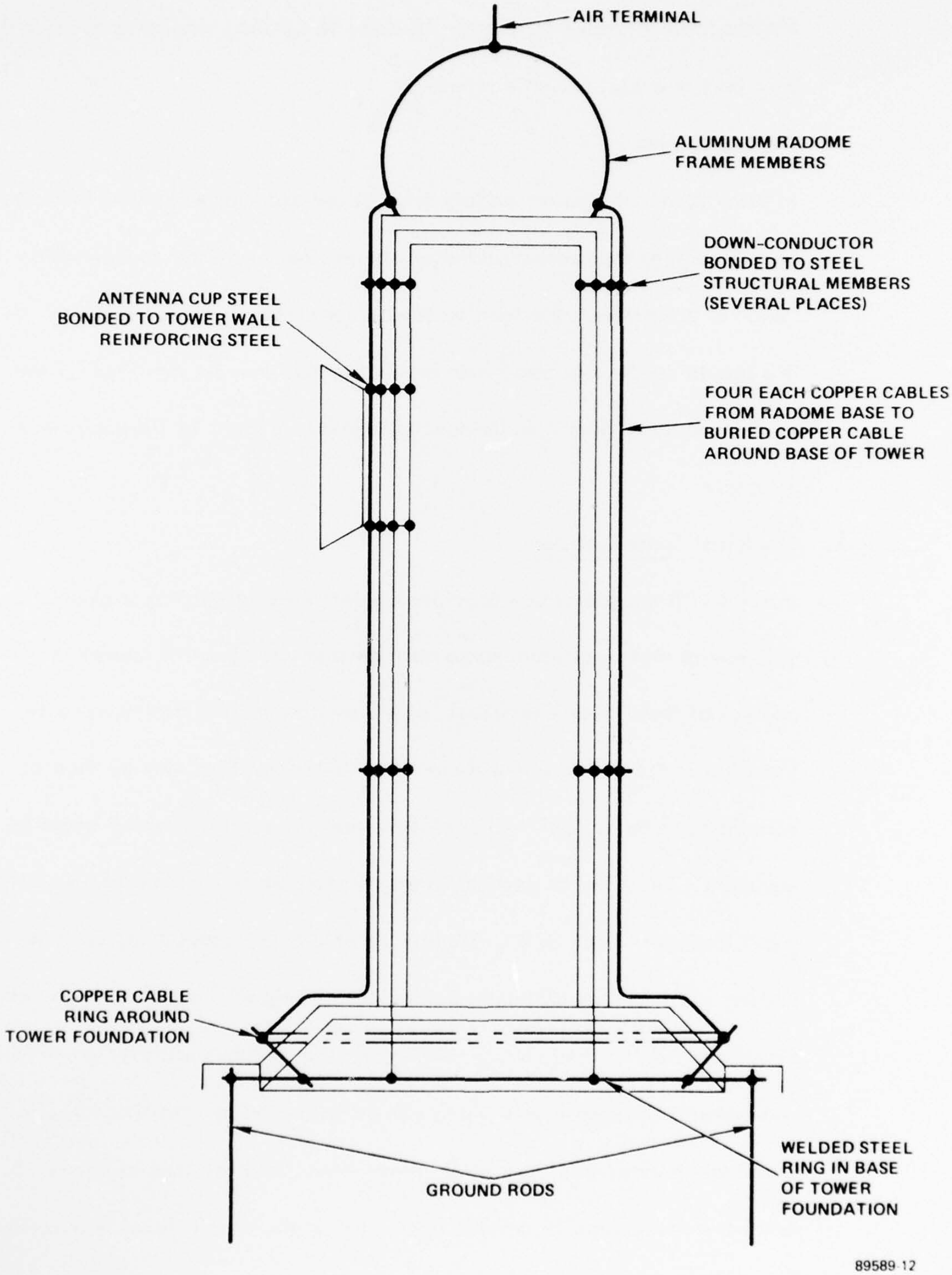

Figure 12. Lightning Protection for Tower-Mounted Antennas

transportable structure here is to illustrate this point, since a radome could be a part of a transportable terminal.

4. Power Modules

In many cases, the power module (engine generator or whatever) is located near enough to the protected antenna or equipment shelter to fall within the "cone of protection" provided by the air terminals on those structures. If this should not be the case, then an air terminal may be provided for the power module to give it individual protection. Figure 14 illustrates this principle.

5. Electrical Surge Arrestors

If even with the protection provided against direct lightning strokes it is determined that significant surge currents and voltages will appear on power and signal lines, then Electrical Surge Arrestors (ESA's) may have to be installed at the points where these currents and voltages may be shunted harmlessly to earth, before they reach sensitive circuitry which could be damaged. Examples of surge arrestors are the familiar carbon block, ball gap, gas-filled spark gap, SCR's, diodes, zener diodes, capacitors, voltage-variable resistor's, as well as EMI-type power line and signal line filters. The above are oftentimes used in conjunction with each other to limit initially great voltages and currents to those levels which can be withstood by sensitive circuits. One such device, used to protect power lines, is illustrated in Figure 15.[15] Another scheme used to provide protection at the circuit level is shown in Figure 16.

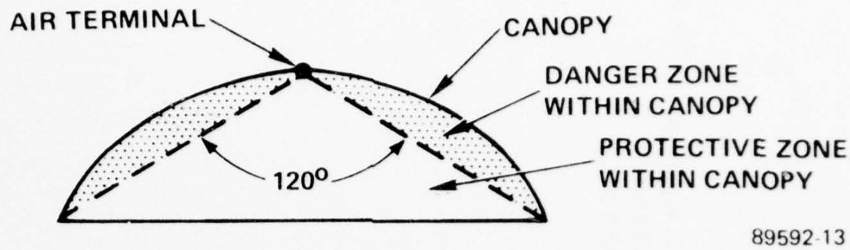

Figure 13. Sectional View Showing Inadequate Protective Zone Created Within Canopy With Too Low an Air Terminal

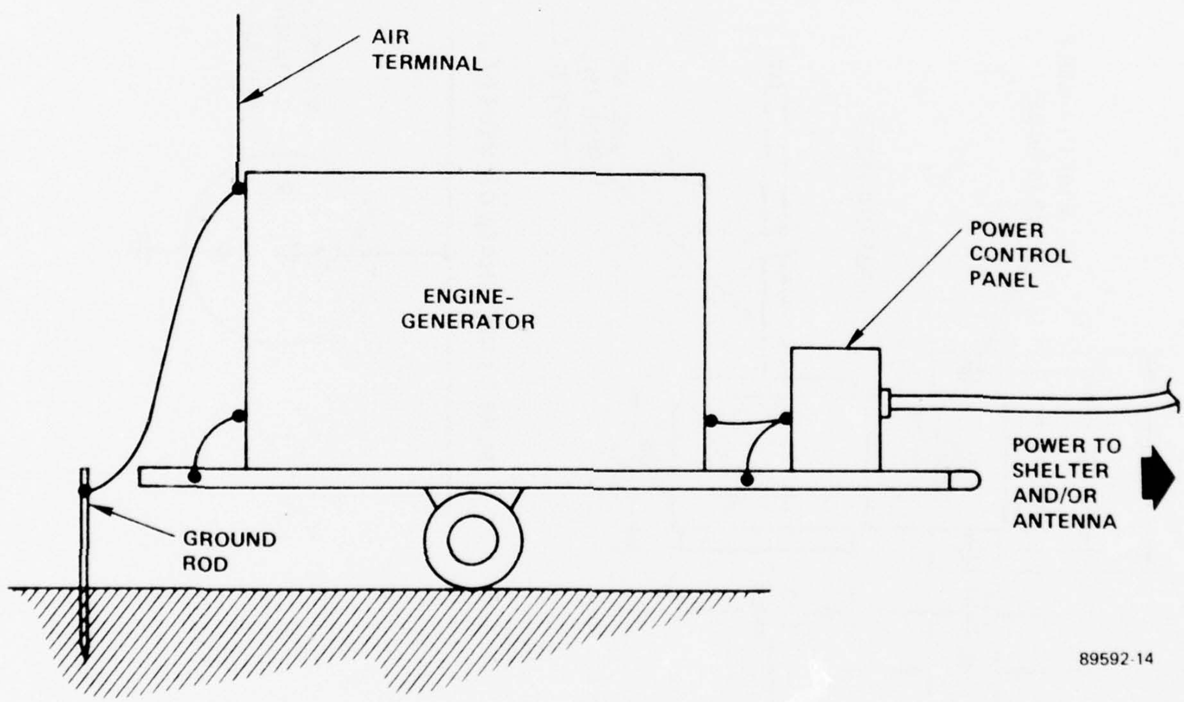

Figure 14. Lightning Protection for Power Modules

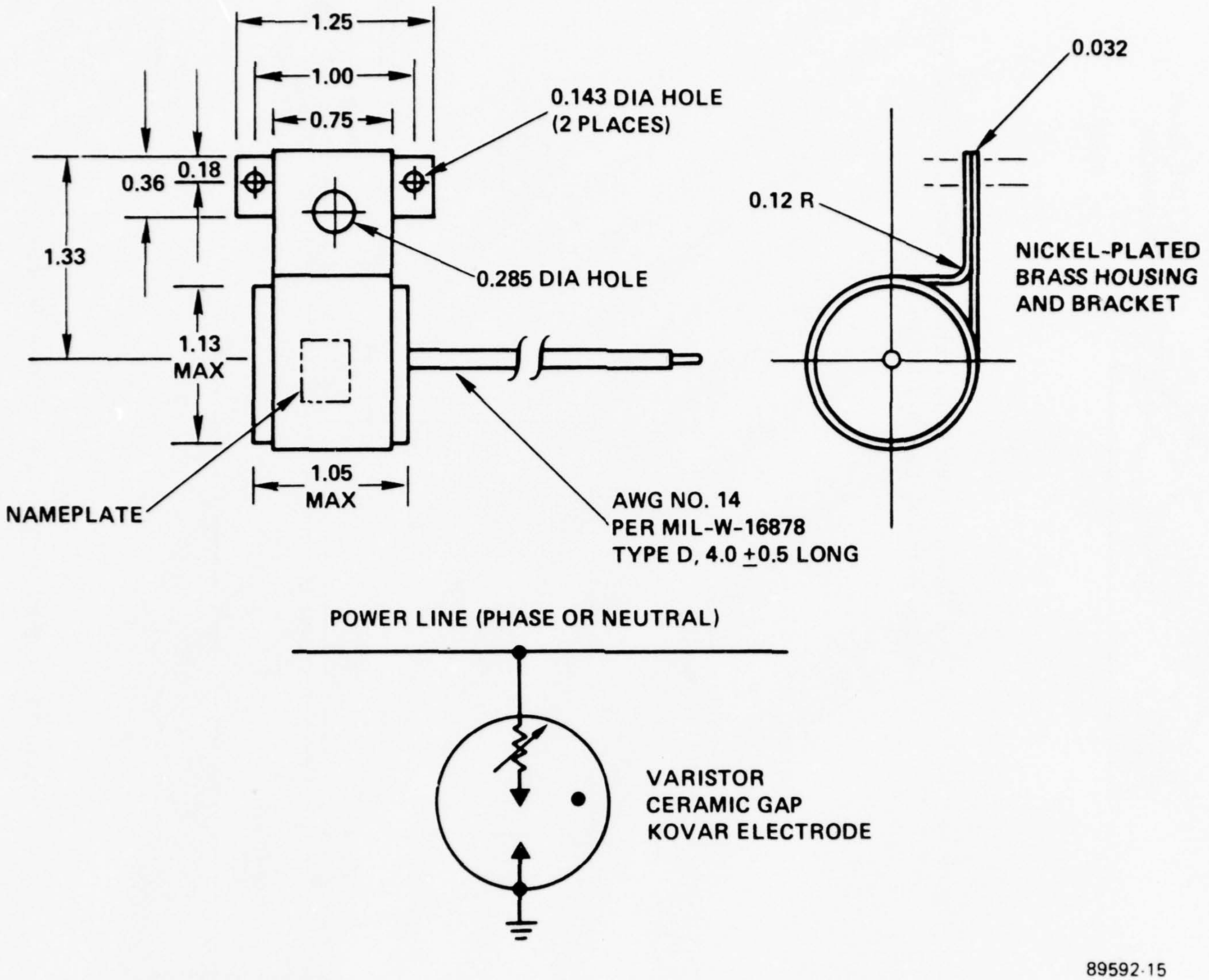

Figure 15. ESA Configuration and Schematic

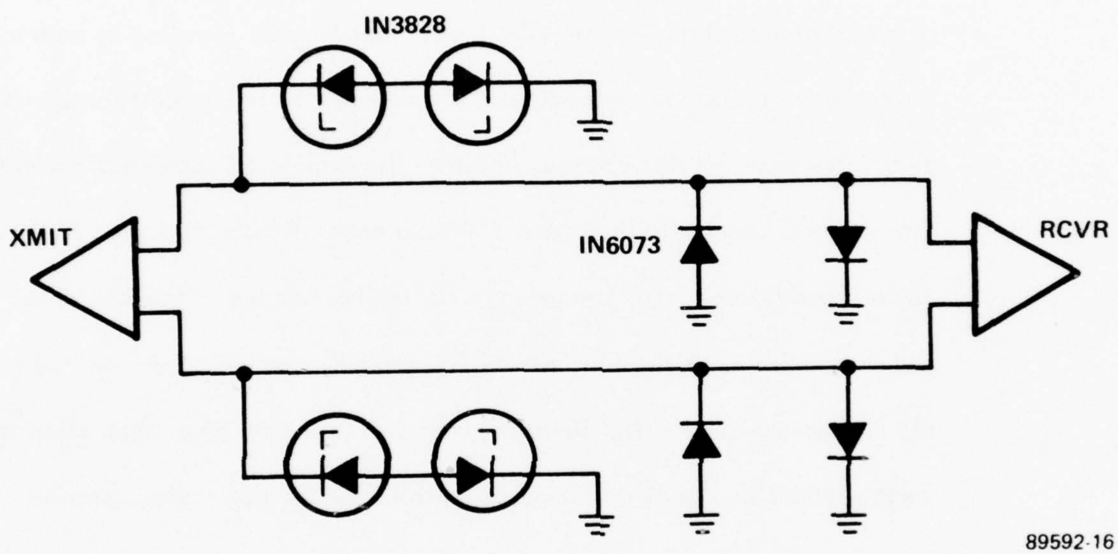

Figure 16. Circuit Level Surge Protection

How these devices are selected is the subject for an entire paper in itself and will not be gone into here. Suffice it to say that there are many parameters which must be considered, the most important two of which are the ability of the circuitry to function properly with the protection device attached and the energy handling capability of the device itself. The most essential aspect of any of these devices is that they be installed in such a manner as to present an extremely low impedance at the highest frequency associated with the disturbance, and that the associated currents are diverted directly and harmlessly to earth. ESA's on power lines are located at the power Input/Output (I/O) panel, which itself is bonded to the shelter (or power module) metallic skin, to which a ground conductor is connected to the site ground field. The lightning rods also will provide a connection to earth. ESA's on signal lines may be installed at the point of penetration into the shelter (or antenna-mounted equipment), as well as further down into the actually equipment racks, chassis, modules, or circuits.

C. EMP Protection

To a large extent the practices used to protect transportable SATCOM terminals against the effects of direct strokes of lightning will also provide protection against EMP. The most significant differences are that the structures themselves and the associated cabling act as antennas which can pick up significant peak currents as a result of "receiving" the energy associated with the EMP, and that there is significant energy out to much higher frequencies. Therefore, more attention must be given to providing low-inductance paths for the EMP-related currents to flow to earth.

1. Antenna Structures

All metallic members of the antenna structure itself - supports, tie downs, joints, grounding system components - as well as antenna-mounted equipment, such as data boxes, junction boxes, azimuth and elevation drive motors, actuators, and gear boxes, must be bonded together into a low-electrical-impulse-impedance mass which is intimately connected to the earth grounding system. All joints must be electrochemically compatible and protected against the elements.

Areas at which mechanical members interface should be free of nonconductive material such as paint, oil, grease, etc., and may be treated to provide an electrically conductive mating surface. Irridite provides such a surface.

2. Equipment Shelters

All joints, I/O panels, air intake and exhaust panels, access ports, and doors must be treated to provide continuous conductive surfaces throughout. This prevents EMP-induced skin currents from producing potentially-harmful fields at points of discontinuity. The shelter ground stud must be connected to the site ground field using as low an impedance path as feasible.

3. Power Modules

The same requirements which apply to Equipment Shelters also apply to power modules.

4. Electrical Surge Arrestors

The same types of Electrical Surge Arrestors (ESA's) which were used for protection against lightning-induced voltages and currents may be used for

protection against EMP-induced voltages and currents. Care must be taken to determine if the protection circuitry can withstand higher residual energy levels downstream from the ESA. This is because the firing point of ESA's of all types is a function of the rise time of the impinging waveform and because the rise time of EMP-induced transients is much shorter than lightning-inducted transients.

5. Cable Shields and Connectors

Cable shields must be as continuous as feasible, solid rather than braided if possible, and must be peripherally bonded to connectors which maintain the shielding effectiveness of the cable shield at both the cable shield end and at the I/O panel, so that EMP-induced currents on the shields may be "stripped" or "combed" off at the I/O panel and directed harmlessly to earth. Connectors must obviously interface at conductively-plated surfaces.

6. Cable Routing

All cabling between the Antenna and the Equipment Shelter should be bundled together and routed over a site ground field which is located as centrally as possible between the two terminal elements. The purpose of this is to reduce loop areas presented by the various cables in order to minimize the pickup of EMP-induced currents. All cable connections should be made to the same side of the shelter to minimize shelter skin currents.

D. Personnel Safety

Incorporation of the above techniques for reasons of system performance, lightning protective and EMP protection to a great extent assures that all metallic objects and structures

which comprise a transportable SATCOM terminal will be at or near equipotential voltage levels - thus rendering those structures safe for personnel to work in, on, and about.

5.0 TYPICAL INSTALLATIONS

Figure 17 illustrates a recent transportable SATCOM terminal upon which both lightning and EMP requirements were imposed. Several items to note have to do with the routing of cables (including the grounding conductors), the central location of the site ground field, the lightning protection on the shelter, but especially the lightning protection on the antenna. Since the antenna was required to provide 360° of azimuth rotation and 90° of elevation adjustment, one air terminal was located on the upper edge of the parabolic dish, and another on the feed, perpendicular to the dish, of such a length and in such a manner as to provide the required cone of protection (120° included angle) regardless of antenna orientation. At the base of each air terminal (which was electrically connected to the antenna at that point), an AWG 4/0 insulated copper conductor was attached and routed between the two air terminals, and another was attached and routed to an insulated terminal located above the azimuth plane. A single AWG 4/0 insulated copper conductor was routed through the azimuth cable wrap to the base of the antenna pedestal and terminated at a single earth electrode (ground rod), driven full depth (minimum exposed portion) into the soil beneath the antenna. The ground rod was 10 feet in length (two 5-foot sections), 0.75 inch diameter, copper-clad steel. The lightning rods were constructed of copper-clad steel, and each rod had a tapered point.

The shelter lightning ground system consisted of two air terminals (lightning rods) located on diagonally-opposite upper corners of the shelter. Each rod was of sufficient length to completely enclose all surfaces of the shelter within a cone of protection from either or both of the rods. Each lightning rod was firmly attached to the shelter structure via a welded receptacle. An

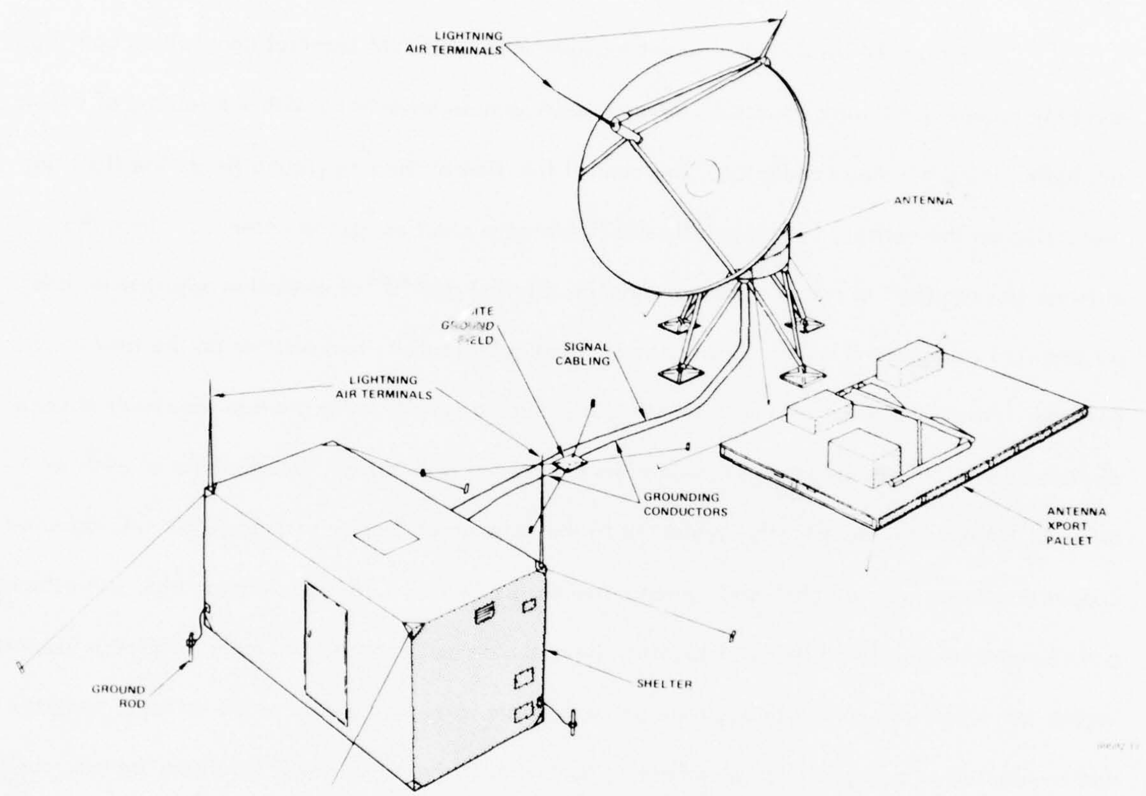

Figure 17. Typical SATCOM Terminal

independent AWG 4/0 insulated copper conductor was connected to the lower section of the diagonally-opposite corners to terminate on individual earth electrodes (ground rods) beneath. The ground rods were identical to that beneath the antenna. The site ground field is illustrated in Figure 18. The ground field was located in as central a position as practical between the Shelter and the Antenna. It consisted of five copper-clad ground rods, 3/4 inch in diameter, and 10-feet long (sectionalized), on approximately 10-foot spacing, in a pentagon configuration. A 1/2-inch thick copper plate 8 inches wide by 13 inches long was located in the approximate center of the pentagon. Connections between rods and between the rods and the plate were made with AWG 4/0 copper cable. An AWG 4/0 copper cable connects the copper plate to the shelter ground stud, and to the antenna ground plate using the most direct run possible.

Spark gaps are installed on the inside of the power input panel on the AC power conductors to limit the surge currents into the shelter power line filters. Back-to-back zener diodes are installed on the inside of the signal input panel between each of the command lines and the command return lines. A 3.9 μF, 10-volt, solid-electrolyte tantalum capacitor was installed on the inside of the signal input panel between each of the status lines and the status return line.

Figure 19 shows an isometric view of another SATCOM Terminal with the same-sized equipment shelter but with a much different antenna configuration. The site ground field was the same as illustrated in Figure 18. The shelter lightning protection was the same as discussed for the previous installation. The ESA's installed at the equipment shelter were also the same as discussed earlier. The antenna structure, however, is significantly different and the antenna of much greater size and different design. Lightning protection is provided by locating two air terminals

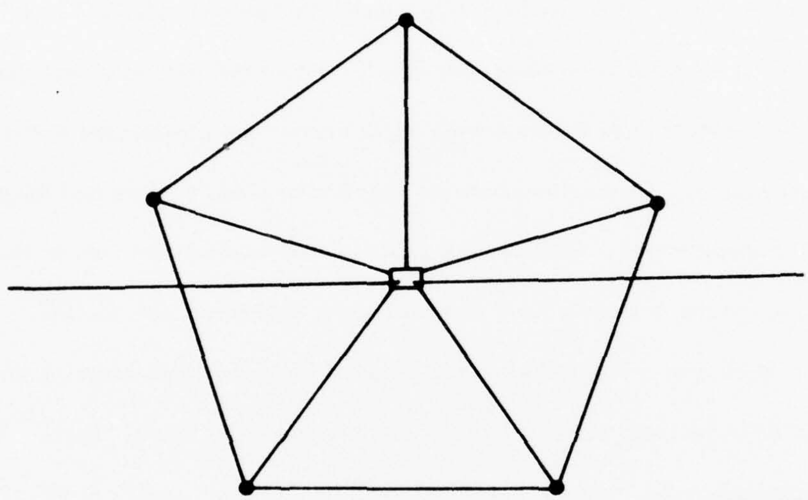

Figure 18. Site Ground Field - Typical (Plan View)

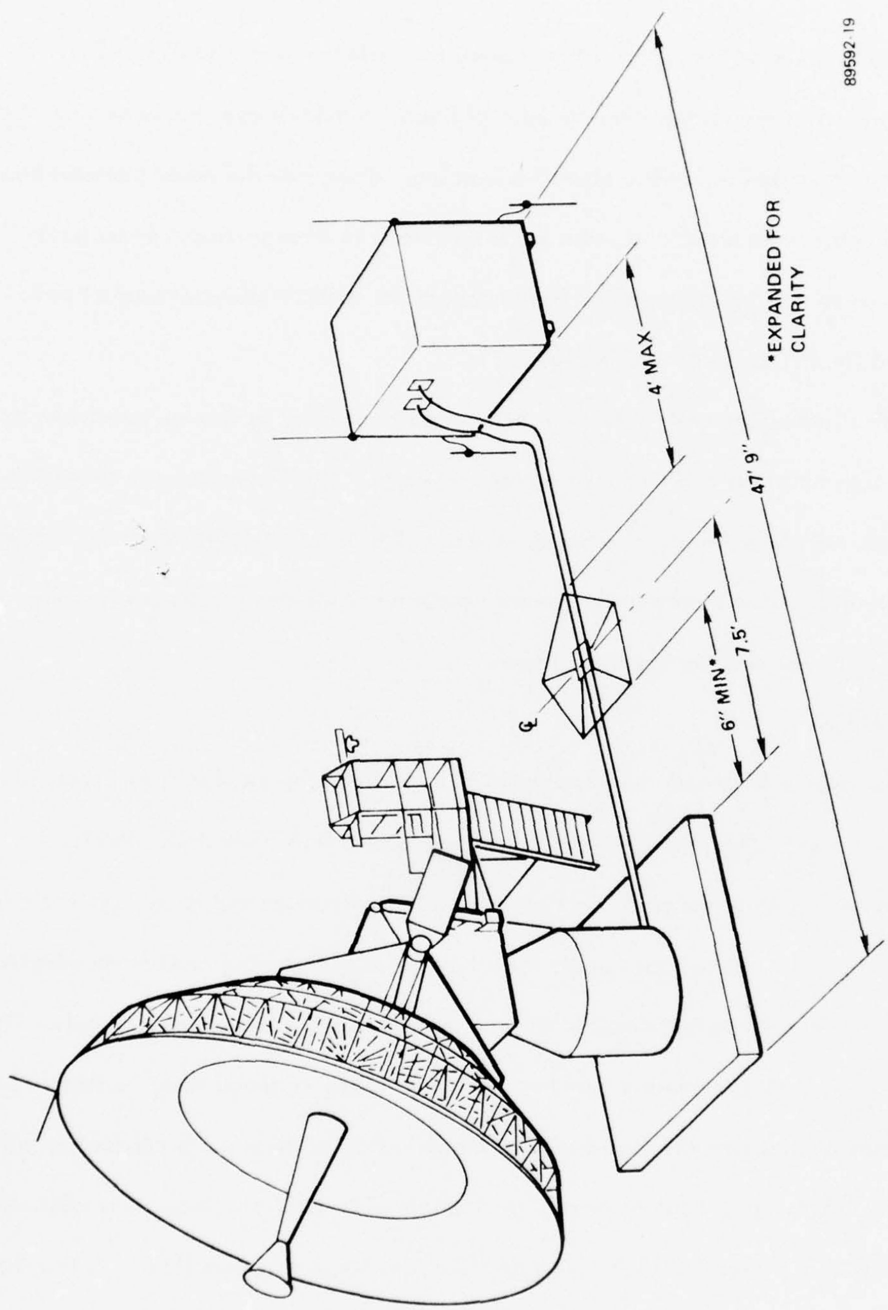

Figure 19. Large Antenna SATCOM Terminal

at right angles to one another at the uppermost portion of the reflector (Refer to Figure 20). Insulated AWG 4/0 copper conductors are routed from the base of the air terminals over the back side of the reflector, into the hub area and across the elevation bearings, down into the upper pedestal base which comprises the cable wrap area, and down the inside walls to through-studs conveniently-located for connection to the lightning ground field beneath the antenna pedestal support pad. The lightning ground field is as illustrated in Figure 21.

In both illustrations every effort has been made to provide as low an impedance path as possible for both lightning and EMP-induced currents to earth. The larger antenna structure, because it has its own AC power input, also has spark gap ESA's installed at its power I/O panels. In addition, because of the open nature of the antenna pedestal, EMI-type filters are installed in front of exhaust fan motors within the upper structure.

6.0 SUMMARY

A great deal is known of the phenomena of both Lightning and EMP, and protective measures have been and are being devised to protect people and objects from their effects.

The same principles which protect power lines, smokestacks and chimneys, radio and TV transmission towers, trees, houses, and boats from the effects of lightning need to be adapted and incorporated to the greatest extent possible to protect transportable SATCOM terminals. This includes the installation of air terminals to provide adequate "Cones of protection," suitability-sized down-conductors to minimize the impedance of the path to a suitable earth connection which usually consists of one, but may consist of several ground rods. In addition, analysis is required to determine if any additional protection in the form of Electrical Surge Arrestors (ESA's) is required

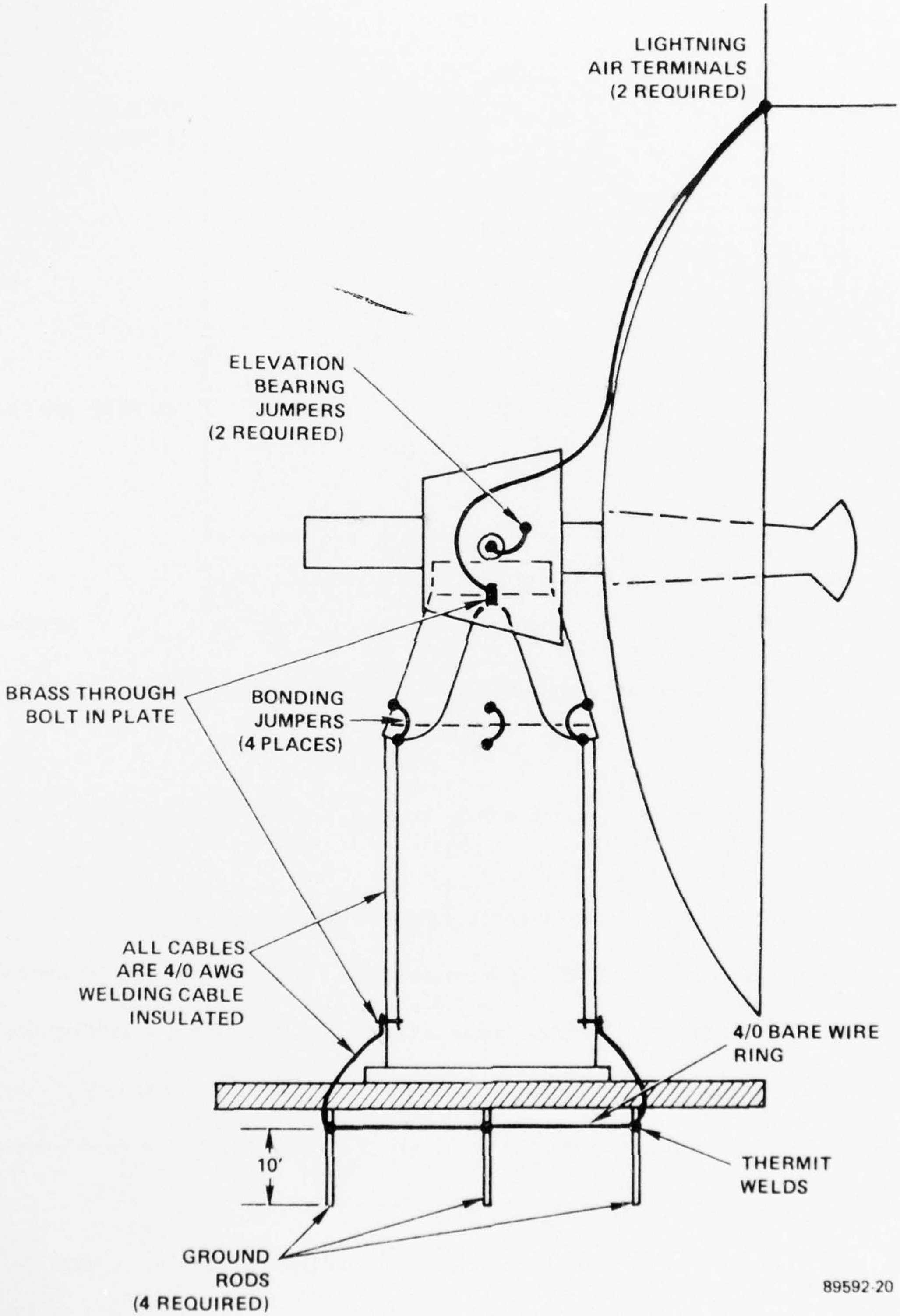

Figure 20. Lightning Protection of Large Antenna

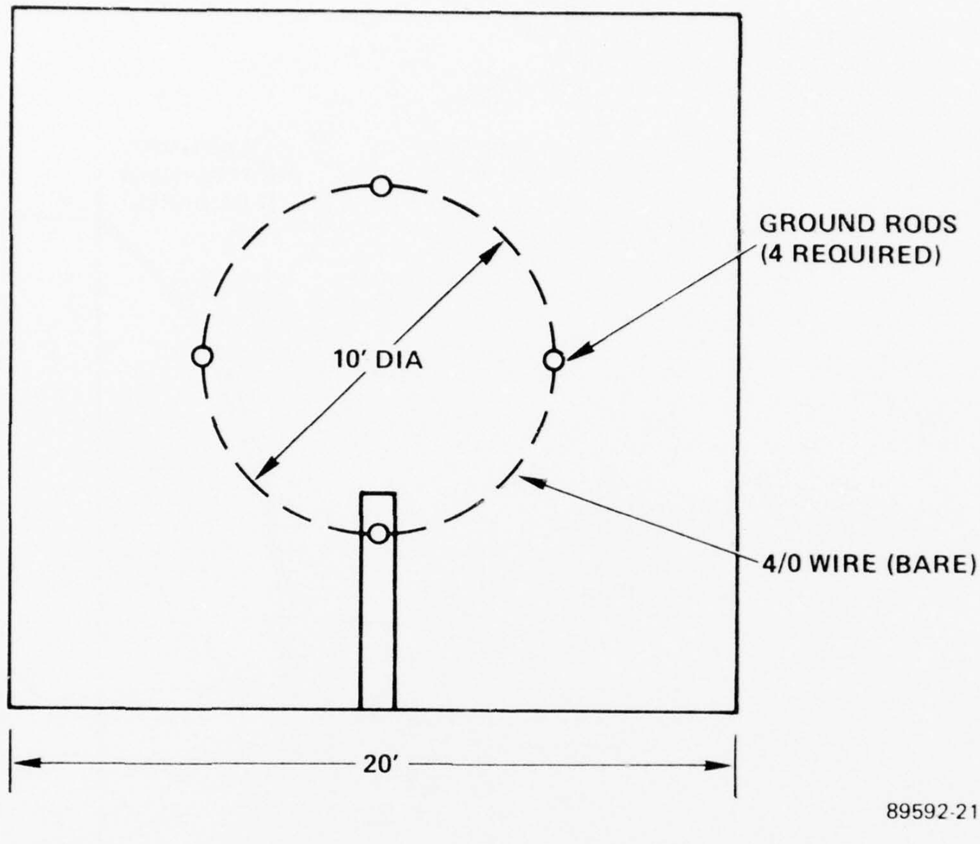

Figure 21. Lightning Ground Field for Large Antenna

on power and signal lines. The devices must be located in the proper place and installed in the correct manner.

The practices used as protection against lightning also serve to provide a measure of protection against the effects of EMP, but because of the significantly higher frequency spectrum involved, attention to the details of low impedance bonding, grounding, shield termination, and connector interfaces are of much greater importance. Also, the rate of rise of the surge becomes very important due to its effect on the firing voltage of ESA's. A very low impedance connection between the ESA and earth also takes on greater importance.

In conclusion, if there is one aspect of both lightning protection and EMP protection which stands out to be crucial above all others, I believe that to be effective grounding.

BIBLIOGRAPHY

DNA-2113H-1, DNA EMP (Electromagnetic Pulse) Handbook, Design Principles (Confidential), Vol. 1. Washington, D. C.: Defense Documentation Center, November 1971.

DNA-2113H-2, DNA EMP (Electromagnetic Pulse) Handbook, Analysis and Testing (Confidential), Vol. 2. Washington, D.C.: Defense Documentation Center, August 1974.

DNA-2113H-3, DNA EMP (Electromagnetic Pulse) Handbook, Environment and Applications (Secret), Vol. 3. Washington, D.C.: Defense Documentation Center, April 1972.

Joslyn Spark Gap, Joslyn Technical Data Sheets. Goleta, California: Joslyn Electronic Systems, August 1972.

MIL-B-5087B (ASG), Bonding, Electrical, and Lightning Protection for Aerospace Systems. Washington, D. C.: U.S. Government Printing Office, 31 August 1970.

MIL-E-6051D, Electromagnetic Compatibility Requirements System. Washington, D.C.: U. S. Government Printing Office, 5 July 1968.

MIL-STD-461A, Electromagnetic Interference Characteristics Requirements for Equipment. Washington, D. C.: U. S. Government Printing Office, 9 February 1971.

MIL-STD-462, Measurement of Electromagnetic Interference Characteristics. Washington, D. C.: U. S. Government Printing Office, 9 February 1971.

MIL-STD-1541 (USAF), Electromagnetic Compatibility Requirements for Space Systems. Washington, D. C.: U. S. Government Printing Office, 15 October 1973.

MIL-STD-1542 (USAF), Electromagnetic Compatibility (EMC) and Grounding Requirements for Space System Facilities. Washington, D. C.: U. S. Government Printing Office, 15 April 1974.

NFPA No. 78, Lightning Protection Code. Boston, MA.: National Fire Protection Association, 9 December 1969.

USPS Marine Electronics Course. New York, N. Y.: USPS Committee for Elective Courses, 1975.

VDE 0875/7.71, Regulations for the Radio Interference Suppression of Appliances, Machines and Installations for Rated Frequency from 0 - to 10 Kc/s. Berlin, West Germany: Verband Deutscher Electrotechniker, July 1971.

FOOTNOTES

1 MIL-STD-1541 (USAF), Electromagnetic Compatibility Requirements for Space Systems. (Washington, D. C.: U. S. Government Printing Office, 15 October 1973), Paragraph 4.0.

2 MIL-STD-1542 (USAF), Electromagnetic Compatibility (EMC) and Grounding Requirements for Space System Facilities. (Washington, D. C.: U. S. Government Printing Office, 15 April 1974), Paragraphs 4, 5, 6 and 7.

3 MIL-B-5087B (ASG), Bonding, Electrical, and Lightning Protection for Aerospace Systems. (Washington, D. C.: U. S. Government Printing Office, 31 August 1970), Paragraphs 3 and 6.

4 MIL-STD-461A, Electromagnetic Interference Characteristics Requirements for Equipment. (Washington, D. C.: U. S. Government Printing Office, 9 February 1971), (Notice 4), Paragraphs 4,5 and 6.

5 MIL-STD-462, Electromagnetic Interference Characteristics Measurement Of. (Washington, D. C.: U. S. Government Printing Office, 9 February 1971), (Notice 3), Paragraphs 4 and 5.

6 MIL-E-6051D, Electromagnetic Compatibility Requirements System. (Washington, D. C.: U. S. Government Printing Office, 5 July 1968), (Amendment 1 - USAF), Paragraphs 3 and 4.

7 VDE 0875/7.71, Regulations for the Radio Interference Suppression of Appliances. Machines and Installations for Rated Frequency from 0 to 10 Kc/s (Berlin, West Germany: Verband Deutscher Electrotechniker, July 1971), Paragraph 4.0.

8 DNA-2113H-1, DNA EMP (Electromagnetic Pulse) Handbook, Design Principles (Confidential), Volume 1,(Washington, D. C.: Defense Documentation Center, November 1971), Sections 6, 7 and 8.

9 DNA-2113H-2, DNA EMP (Electromagnetic Pulse) Handbook, Analysis and Testing (Confidential), Volume 2, Washington, D. C.: Defense Documentation Center, August 1974), Section 9.

10 DNA-2113H-3, DNA EMP (Electromagnetic Pulse), Handbook, Environment and Applications (Secret), Volume 3, Washington, D. C.: Defense Documentation Center, April 1972, Section 17.

11 MIL-B-5087B (See Note 3).

12 NFPA No. 78, Lightning Protection Code (Boston, Mass: National Fire Protection Association, 9 December 1969), Paragraph 2600.

13 USPS Marine Electronics Course, (New York, N. Y.: USPS Committee for Elective Courses, 1975), Section 1.7.

14 MIL-B-5087B (See Note 3).

15 Joslyn Spark Gap, Joslyn Technical Data Sheets (Goleta, California: Joslyn Electronic Systems, August 1972), P/N 2301-38.

THEORETICAL ANALYSIS AND DESIGN TECHNIQUES FOR GROUNDING TO ACCOMPLISH EMI CONTROL

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

The proper grounding is one of the most important considerations for Electromagnetic Interference (EMI) control. The analysis and the test results of complex electrical and electronics systems have shown that the majority of the Electromagnetic Compatibility (EMC) problems are directly attributed to the existing absolute grounding systems.

All the system electrical and structural components must be maintained at the same reference potential in order to accomplish interference suppression through an effective grounding system. The basic objective of the grounding is to prevent the transfer of any generated electromagnetic interference from one component to another component of the system. In addition, the safety of the personnel and the electrical and electronics systems must be considered. This objective is accomplished by designing one or several grounding planes combined at one common reference point. In airborne systems the ground provisions are made using the airframe. The common reference point is provided by the earth grounding for the land installations.

The effectiveness of the grounding system is often dependent upon the methods used for bonding. The theoretical analysis of the bonding jumper parameters at RF frequencies is made for low impedance requirements.

THEORETICAL ANALYSIS AND DESIGN TECHNIQUES FOR GROUNDING TO ACCOMPLISH EMI CONTROL

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Sunnyvale, California

The proper grounding is one of the most important considerations for Electromagnetic Interference (EMI) control. In the past the term grounding has been used in the additional sense of utilizing structure as the return path for completing the circuits. This has been common practice in the aircraft and automobile industry, but with the advent of much more sophisticated and sensitive systems, utilization of properly designed ground has become one of the basic requirements. The analysis and the test results of complex electrical and electronics systems have shown that the majority of the Electromagnetic Compatibility (EMC) problems are directly attributed to the existing absolute grounding systems.

All the system electrical and structural components must be maintained at the same reference potential in order to accomplish interference suppression through an effective grounding system. The basic objective of the grounding is to prevent the transfer of any generated electromagnetic interference from one component to another component of the system. In addition, the safety of the personnel and the electrical and electronics systems must be considered. This objective is accomplished by designing one or several grounding planes combined at one common reference point. In airborne systems the ground provisions are made using the airframe. The common reference point is provided by the earth grounding for the land installations.

The effectiveness of the grounding system is often dependent upon the methods used for bonding. The theoretical analysis of the bonding jumper parameters at RF frequencies is made for low impedance requirements.

EARTH GROUNDING

The earth grounding must provide a low impedance path to all frequencies to the soil beneath the installation. The soil resistivity changes by the following parameters:

1. The moisture content of the soil.
2. Type of soil (clay, sand, gravel, rocky).
3. Temperature
4. Diameter and depth of the rods.
5. Material of the rods (copper-clad is preferred).

Prior to the construction of the installation the soil condition of the site should be determined and design of the earth grounding should be conducted accordingly. The ground rods, 3/4 inches in diameter or larger, driven into the permanent water table will usually provide an earth connection of 0.5 ohms or less. It is recommended that the grounding rods should be driven at least 30 feet deep. The resistance to earth measurements of the grounding rods should be conducted during the installation and periodically afterward [1] .

GROUND RESISTANCE MEASUREMENTS

The ground resistance measurements can be presented in the following four groups [2]

(1) The RF (radio broadcast) method. This method is used primarily when the conductivity of the soil between two points spaced over a distance of fifteen miles or greater is to be determined. Some special RF equipment is required for this measurement.

(2) The three-point method. In addition to grounding rod under test two auxiliary electrodes are used. The resistance to earth of the rod and the auxiliary electrodes are measured two at a time in series. This is possibly the simplest method requiring only an ohmmeter or resistance bridge and a few simple calculations. For accurate results the resistance of the ground rod and the auxiliary electrodes should be in the same order of magnitude. This method is not suitable for the measurement of low resistance grounds.

(3) The fall-of-potential method. Two remote reference grounds are used for this measurement. The method involve passing a known ac current through the grounding rod under test and one of the reference ground at a time. The potential drop is recorded each time while the same amplitude of current is maintained. The resistance is calculated by using the value of the known current.

(4) The ratio method. A modified wheatstone bridge principle is used for this method by utilizing two auxiliary electrodes or reference ground points. The ground rod resistance in series with one auxiliary electrode is measured by using a bridge. The ratio of the resistance to earth of the first auxiliary electrode to the resistance of the grounding rod in series with the second auxiliary electrode is determined. Multiplying this ratio by the series resistance measured above gives the earth resistance of the grounding rod. A specially designed and manufactured instrument called Vibraground is commercially available for this purpose.

GROUND PLANE

The ground plane is defined as a metal sheet or plate used as a common reference point for all associated systems. The ideal ground plane would provide to all equipment a common potential reference (zero-potential, zero-impedance system) point so that no voltages exist between any two points anywhere in the system. The ideal ground plane for a facility should consist of a continuous sheet of copper. This is not practical and is very

expensive for large facilities, therefore a grid of (10 X 10 feet) brazed or welded heavy copper conductors (#2/0 AWG or larger) should be used. This grid should extend at least 6 feet beyond the building walls. The dc resistance or impedance to earth must be maintained very low by using adequate grounding rods. The copper-clad grounding rods are preferred because the primary conductor is made using high-purity and high-conductivity copper and a steel core is used for strength.

The radial ground system is very effective to dissipate currents from interference sources into earth [3]. A general arrangement of the radial system shown in Figure 1 is designed to provide a very low impedance path to the earth for RF currents. This system consists of six radial perimeter rods, (one-inch thin-wall copper tubing), spaced 60 degrees apart, and a center rod which is larger than the perimeter rods. The perimeter rods are driven 30 feet and the center rod is driven 40 feet into the earth. The perimeter rods are connected to the center rod using 12 feet conductors, brazed at the joints.

GROUNDING CONDUCTORS

Skin effect is one of the main reasons for the high impedance of conductors at RF frequencies. This becomes more noticeable if stranded cables are used where the self-inductance of the cable increases as frequency increases. Therefore, above 1000 Hz the stranded conductors should not be used.

Solid conductors should be used if the system operational frequencies are above 1 GHz. For medium and low level currents round solid conductors and for large amount of currents flat conductors or copper tubes are recommended. The edges of the flat conductor should be rounded (elliptical cross section) so that the antenna effect of the corners will be minimized.

METHODS OF GROUNDING

To avoid interference between various system functions the modern facilities have many separate grounding systems, such as signal grounds, shield grounds, structural grounds, lightning grounds, ac power primary and secondary grounds. The grounding system design should consider the operational parameters (type and levels of the signals, external electromagnetic environment) and the geometry (distances between equipment, cabling design, metallic building structure) of the system. A high frequency oriented small system may require a multiple-point grounding system. For a large system utilizing digital equipment, single-point grounding may be adequate. Regardless of the grounding approach selected, grounding, bonding, wire routing and shielding must be considered simultaneously for an optimum design.

Single-point grounding. The single point grounding is defined as the connection of return (reference) lines to one isolated ground point in such a way that the undesirable common mode impedance coupling is eliminated [4]. For an ideal facility grounding system separate grounding system separate grounding buses extend from a single point on the earth counterpoise. The signal returns of each system are connected to these ground buses as shown in Figure 2a and Figure 2b.

The system level single point ground may be accomplished by using one of the following two methods or by combining these two methods.

(1) Common reference point for separate system power supplies. In this design the return of each system power supply is referenced to the same point in the system as shown in Figure 2a. The same reference point for the system could be provided by using an isolated ground stake or by using a common uni-potential ground plane with several ground stakes. This grounding method is similar to multiple point grounding except that the ground plane used in a multiple point method is not specified as a uni-potential ground plane. This method is suitable for large facilities provided that the voltage drops on reference lines are balanced and capacitive and inductive coupling of undesirable energy on long reference lines are minimized.

(2) Use of common power supply. This method utilizes a single central power supply for the entire system. All returns are terminated at the single power supply. It is desirable that all power and signal lines in the system are routed as pairs with the reference point placed at the power supply as shown in Fig 2b.

Multiple-Point grounding. This method utilizes many points on a ground plane for the system reference. The returns of each power supply of the system should be referenced to the ground plane at the respective power supply as shown in Figure 3. The reference ground plane should be designed and maintained at uni-potential configuration as much as possible. An ideal condition would be an extremely large sheet of copper underlying the entire facility. A practical approach is to use a network of conductors to provide several paths within the system. The multiple referencing to the ground has been found to be a good practice, when the system frequency is above one megahertz.

THE SYSTEM GROUNDING

The grounding systems of the facility should be maintained at the same reference potential to accomplish interference suppression through an effective ground. The following separate grounding systems of the installation should be combined at one common reference point (earth plane) so that the potential differences between the system are minimized to eliminate the flow of the interference currents between the parts of the systems. (Reference Figure 4).

AC POWER GROUND

The neutral of the ac power (primary power) must be earth grounded before entering the facility. Any secondary ac power which is derived from the primary power should have its own ground system with the ground returned to the secondary power source. The secondary power ground then should be grounded to the system ground plane.

DC POWER (INSTRUMENTATION) GROUND

The dc return of every dc power supply should be connected separately at one point to the signal ground (technical) counterpoise. Instrumentation ground plates should be provided for sensitive equipment locations, in large facilities. The copper plates at least 6 inches long and 4 inches wide and 1/2 inch thick is recommended. These ground plates should be connected to the counterpoise by an insulated large (number 500 MCM) copper cable, so that the system will be isolated from building structure and other grounds.

STRUCTURAL (STATIC) GROUND

The metallic building structure and all other conductive parts of the system that are not designed to handle current flow forms the structural ground system. The equipment enclosures, pipes, conduits, ducts, and electrical panels should be bonded together to form as many parallel paths as possible. All cable shields should be connected to the structural ground system.

BONDING REQUIREMENTS

Bonding is provided as an electrical joint for the purpose of holding two or more metal structures at a common electrical potential. The most important objective of bonding is to prevent the presence of the potential gradients which will cause the flow of electromagnetic interference currents. In addition, the protection of personnel from the shock hazards is assured by preventing the accumulation of the static charge buildup and by providing fault-current return paths. Bonding should be considered as a parameter in the original installation design. The structural steel of the facility should be adequately bonded so that it is electrically homogeneous. In large installations the cable trays must be bonded together and to the building structure.

There are two general techniques for bonding: Direct and indirect. The direct bonding is accomplished by metal-to-metal contact between two surfaces by welding, brazing, sweating, riveting or bolting. These bonds usually have a low dc resistance and low impedance at high frequencies. A minimum of 2.5 milliohms dc resistance is recommended for direct bonding of joints.

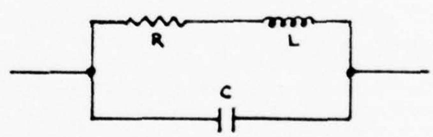
Corrosion between metal surfaces of a bond held together by some means of clamping may cause deterioration of the bond. In time, corrosion may cause the impedance between the surfaces to increase to the point where a bond may be ineffective. Both electrolytic and galvanic types of corrosion occur in the presence of moisture which comes in contact with the mating surfaces. When metallic surfaces are bonded together, they should be free of grease, oil, dust and other types of residues. All electrically insulating finishes should be removed from the surfaces which are to be bonded together. Only the areas of the fastener holes need to be removed when surfaces are to be held together with fasteners. Conductive finishes need not be removed.

The indirect bonding requires the use of bonding jumpers. There is no special design problem at low frequencies. At higher frequencies the length of the jumper should be minimized since the impedance of the jumper is a critical design consideration. For flat jumpers a length-to-width ratio of 5 to 1, with a minimum thickness of 0.025 inch and 1 inch width is recommended.

The effectiveness of bonding should be verified by measurements. In light of the difficulties that exist for impedance measurements at RF frequencies, the practical approach is to make limited dc resistance bonding measurements to determine the quality of bonding installations [5] .

BONDING JUMPER PARAMETERS FOR RF FREQUENCIES

The bonding jumpers have the usual electrical parameters of R, L, C which are determined by the selected material, physical dimensions and configuration. An equivalent circuit for a bonding jumper is shown below:



BONDING STRAP - EQUIVALENT CIRCUIT

$$|Z| = \left[\frac{R^2 + \omega^2 L^2}{(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2}\right]^{1/2} \quad [6]$$

We can neglect R since the value of the bonding jumper resistance in ohms is very small (0.0025 ohms or less).

$$|Z| = \frac{\omega L}{1 - \omega^2 LC}$$

$$\text{or } |Z| = \frac{1}{\omega C}\left(1 - \frac{1}{\omega^2 LC}\right)$$

When: $\omega^2 LC < 1$ the jumper is predominantly inductive.

$\omega^2 LC = 1$ the jumper impedance is maximum (resonant)

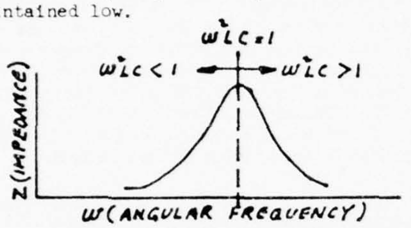
$\omega^2 LC > 1$ the jumper is predominantly capacitive

These relations, which are shown below indicates that to keep the impedance or the bonding jumper low, the value of $\omega^2 LC$ must remain as far as possible from 1. The resonant frequencies of the jumper should be as far away as possible from the system operational frequencies.

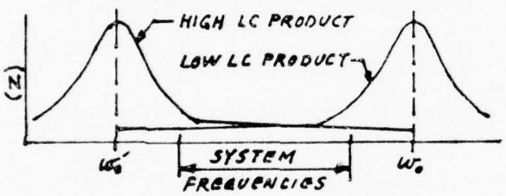
From the expression for resonance

$$\omega_o^2 = \frac{1}{LC}$$

the angular frequency ω_o' and ω_o'' resonant conditions are dependent upon the LC product. For a low ω_o' resonant frequency, the LC product must be large. For a high ω_o'' resonant frequency the LC product must be maintained low.



IMPEDANCE CHARACTERISTICS



RESONANT FREQUENCIES

CONCLUSION

The majority of the system electromagnetic compatibility problems of electrical and electronics facilities are directly related to the poor grounding practices. Therefore, grounding and bonding considerations must play a significant role during the initial design of the facility. The parameters employed in analyzing and designing a proper grounding concept for the installation include operational frequencies, location of the units, and interface criteria.

The design of the earth grounding systems is based upon (1) reference plane grounding system, (2) number of ground rods, (3) depth of the ground rods and (4) soil conditions.

The isolation of the ground problems is accomplished by separate ground systems for (1) static and structural ground, (2) ac power ground, (3) shield ground and (4) dc power and circuit ground. A common ground for both power and signal circuits can cause increased interference pickup in the signal circuit and should be avoided.

The concepts of single-point grounding and multiple point grounding are used to reference the system circuits to a common uni-potential. Single-point grounding for a low frequency systems and multiple-point grounding for high frequency (1 MHz and above) are recommended. In the event of marginal condition single-point grounding should be considered since it is easy to switch from a single-point system to a multiple point grounding, but it is extremely difficult to do otherwise.

The bonding is one of the most important part of the design parameter of the system grounding. For the purpose of the electromagnetic compatibility, in which frequency is such an important consideration, dc resistance alone is not a satisfactory measure of the effectiveness of a bond. Therefore, the LC product of the bonding jumper must be analyzed.

REFERENCES

[1] IEEE Recommended Practice for Grounding, IEEE STD 142-1972.

[2] Standard Handbook for Electrical Engineers, D. G. Fink and J. M. Carrol, New York: McGraw-Hill, 1968

[3] R. Morrison, Grounding and Shielding Techniques in Instrumentation, John Wiley & Sons, Inc., New York, 1967.

[4] G. M. Kunkel, Grounding and Bonding for Computer Systems, presented at the 1971 Computer Designers Conference, Anaheim, California, 1971

[5] RFI Handbook, Fredrick Research Corp., Wheaton, Maryland, 1962

[6] Reference Data for Radio Engineers, Howard W. Sams and Company, Inc., ITT, Fifth Edition, 1968.

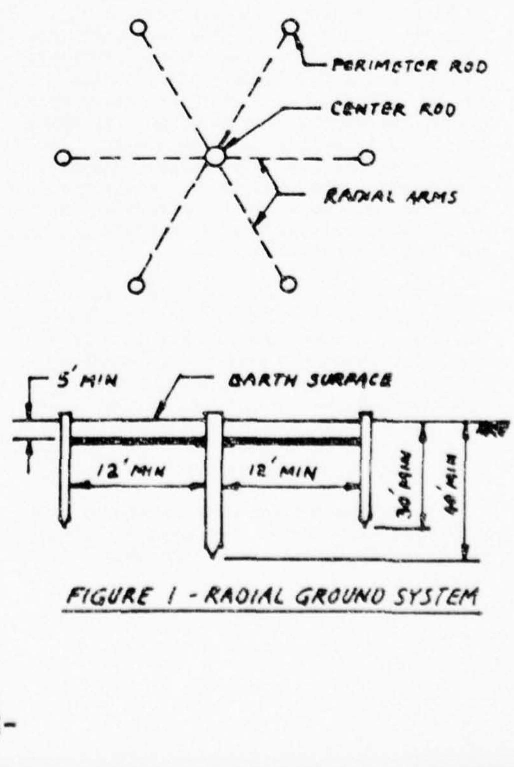
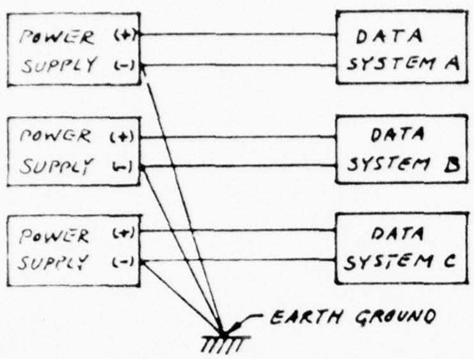
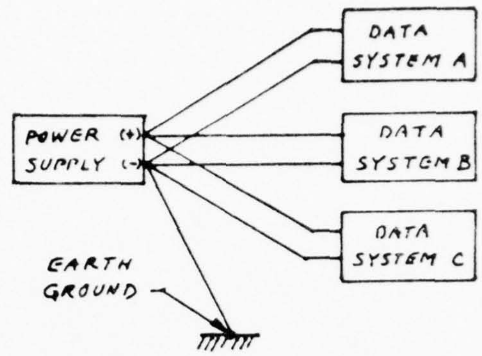


FIGURE 1 - RADIAL GROUND SYSTEM



COMMON REFERENCE POINT
SINGLE - POINT GROUNDING
FIGURE 2a



COMMON POWER SUPPLY
SINGLE - POINT GROUNDING
FIGURE 2b

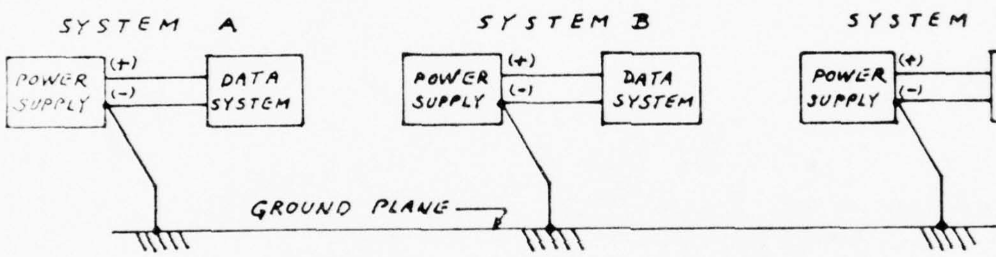


FIGURE 3 - MULTIPLE - POINT GROUNDING

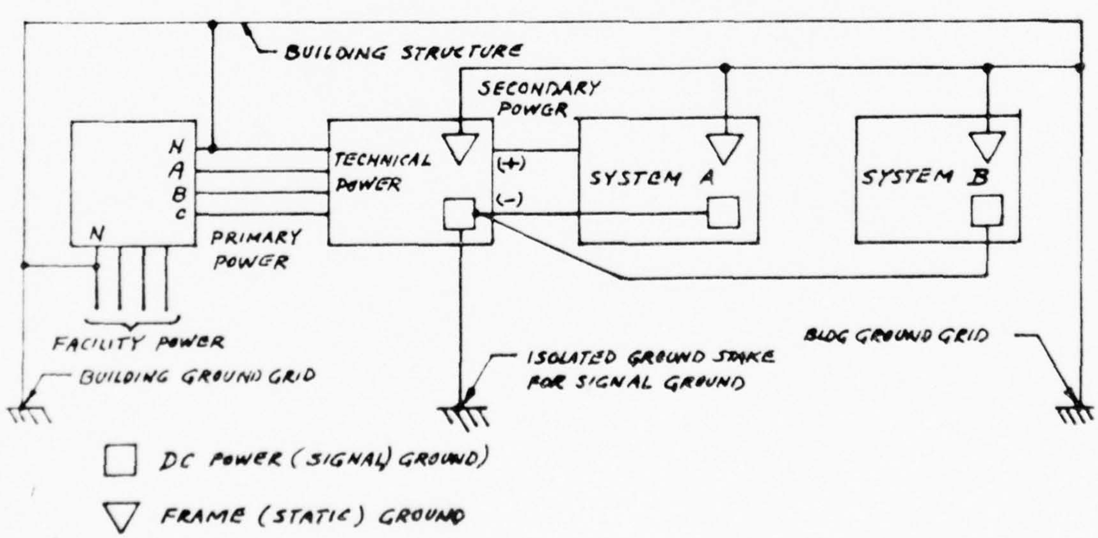


FIGURE 4 - FACILITY GROUNDING SYSTEM

SHIELDING AND GROUNDING TOPOLOGY FOR INTERFERENCE CONTROL

by

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ABSTRACT

Protection of electronic equipment from interference originating from lightning and the nuclear EMP requires that a small-signal environment for electronic equipment be provided even though large transient fields and currents may be developed outside the cabinet or building. A shield may be used to separate the electromagnetic environment inside the cabinet or building from the harsh outside environment. In light of the large iR and Ldi/dt voltages developed in grounding conductors by lightning and the EMP, the shield potentials may vary over a many-kilovolts range; it is not feasible to prevent these fluctuations. However, even though the shield potential varies widely during transient excitation, the potential of everything inside the shield also varies in the same way so that there are no potential differences (except those generated by internal sources) within the shielded region. Undesired potential drifts or fluctuations caused by charge displacements or other internal sources can be controlled by electrically interconnecting all internal conductors with the shield (i.e. "grounding" them to the shield). Thus the shield prevents internal potential fluctuations caused by external sources, and "grounding" controls internal potential fluctuations of internal origin.

In practice, several levels of shielding and grounding may be used. These often consist of a building shield with its internal electrical grounding system, a cabinet shield with its internal electronics grounding system, and perhaps shielded components within the cabinet. At each level, the shielding and grounding topology portrays the shield as a barrier to its external environment and the grounding system as a means of controlling potentials from internal sources.

Also in practice, the shields must be compromised by conductors that carry power and information through the shield and by access doors, ducts, cracks, etc. incumbent in fabricating and servicing facilities or equipment. Application of shielding and grounding topology permits these compromises to be readily identified (even if they are quite subtle); in addition it can be used to determine how filters, surge arresters, and other protective devices should be installed and grounded to preserve the integrity of the shield. Most important, however, is the fact that shielding and grounding topology is useful in explaining some of the interference problems that have been reported, as well as how these problems may be avoided in the future.

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SHIELDING AND GROUNDING TOPOLOGY
FOR INTERFERENCE CONTROL

I INTRODUCTION

Small-signal electronic circuits, whether they use discrete component or integrated circuits, are susceptible to malfunction or damage caused by transient interference. These problems are particularly common in data processing circuits because these circuits often cannot distinguish between a spurious transient and a legitimate signal, and because these circuits are designed for small switching levels to conserve power and reduce heat dissipation problems. Logic levels are often a few volts or a few tens-of-milliamperes in these circuits.

On the other hand, transients associated with lightning and switching on power lines and buried communication cables commonly have peak currents of tens of kiloamperes and peak voltages of megavolts.[1] Similar peak values are associated with the nuclear electromagnetic pulse. Thus if small-signal electronic circuits are to be operated by commercial ac power, in buildings supplied with ac power, or in systems that are interconnected by long buried or overhead cables, it is apparent that the structure between the outside cables or power conductors and the small-signal electronic circuits must be capable of reducing the transients by over 100 dB.

In addition, grounding electrodes such as ground rods, ring grounds, counterpoises, etc. typically have impedances of a few ohms, while grounding electrode impedances of tens or hundreds of ohms are not uncommon. In series with this soil impedance is the inductance of the grounding conductor, which is typically a few microhenries (about 1 μH per meter of ground wire). Thus the Ri + Ldi/dt voltages developed across the grounding impedance when lightning strikes a power line may be of the order of 100 kV even if a good grounding electrode is used. Therefore, as illustrated in Figure 1, even the best electrical grounding practices cannot prevent wide fluctuations in the potential of a building ground point if lightning strikes the building, or if it strikes the power lines or cables near the building.

For electronic systems to operate reliably in this environment, therefore, we must be able to accommodate these wide fluctuations in building ground-point potential and reject the severe transients on external power lines and cables. In addition, however, we must be able to supply power to the electronic circuits and provide means of getting information into and out of these circuits. To achieve these goals, a systematic approach to shielding and grounding is required.

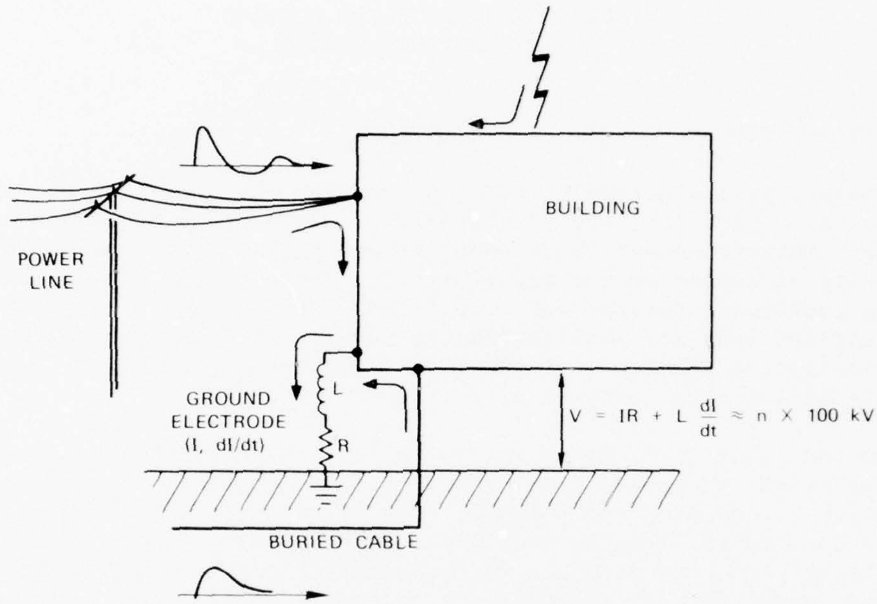
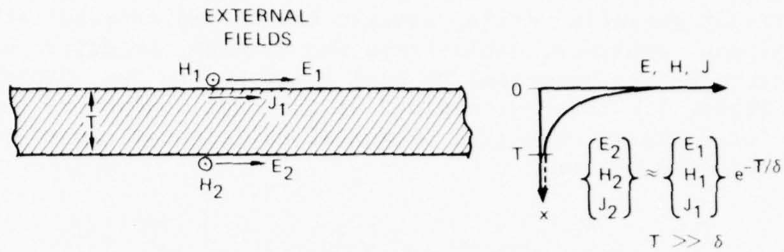


FIGURE 1 BUILDING POTENTIAL PRODUCED BY LARGE TRANSIENTS

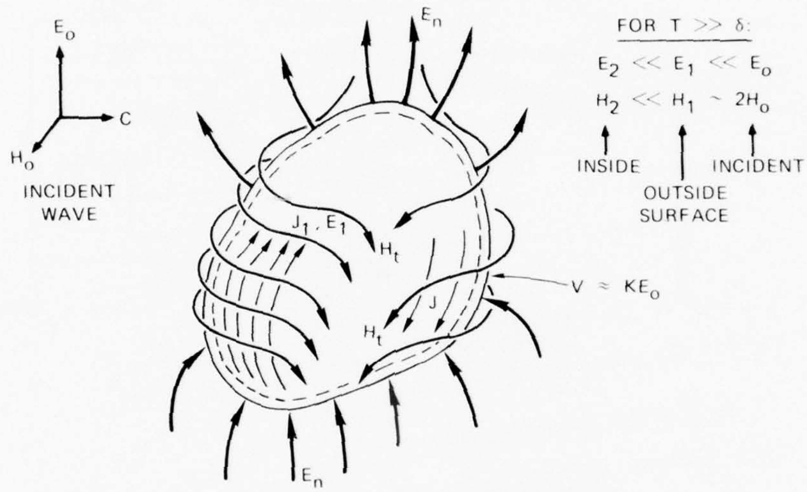
II DEVELOPMENT OF SHIELDING AND GROUNDING PHILOSOPHY

If the walls of the building in Figure 1 are perfectly conducting so that there is no penetration of either electric or magnetic field through the walls, the potential of the entire building and all of the space inside it will be the same, regardless of whether that potential is zero or 100 kV. The importance of this fact is that there are no potential differences within the building even though the potential of the building with respect to the earth may fluctuate widely. The perfectly conducting shield is thus an electrodynamic Faraday shield that isolates the enclosed space from external influences, whether these be fields, currents, or voltages. All external fields are totally reflected by the walls and all current or charge injected on the outside surface remains on the outside surface (the skin depth in a perfect conductor is zero).

If the walls are not perfectly conducting, the external fields are not quite completely reflected, and currents injected on the outer surface penetrate into the walls. Nevertheless, as illustrated in Figure 2, when the wall thickness is large compared to the skin depth δ, the fields (or potential gradients) inside the shield are much smaller than those outside the shield.



(a) DECAY OF ELECTROMAGNETIC FIELDS AND CURRENT DENSITY IN SHIELD



(b) EXTERNAL FIELDS ABOUT A CLOSED SHIELD

FIGURE 2 ELECTRODYNAMIC SHIELD

The electrodynamic shield thus provides a barrier between the external environment and the internal environment. Hence in the region enclosed by an ideal shield there are no gradients or potential differences caused by sources outside the shield. However, there may be gradients in the enclosed region caused by sources or charge displacements within the shielded region. For example, if the building in Figure 1 contains a battery or some other power source, this source can produce gradients or potential differences. Similarly, if there is mechanical motion inside the building, electrostatic charging may occur and produce potential differences. But these potential differences are caused by internal sources; the shield has no effect on them, and they are unrelated to the outside environment.

To control potential differences of internal origin so that they do not pose shock or explosion hazards or induce electrical malfunction because of circuit potential drift, circuit common and internal structures such as equipment cabinets, cable trays and shields, conduits, and other metal structure may be connected to each other and to the shield as indicated in Figure 3. This "grounding" of internal conductors and circuits eliminates (or reduces) undesired potential differences caused by sources inside the shielded region.

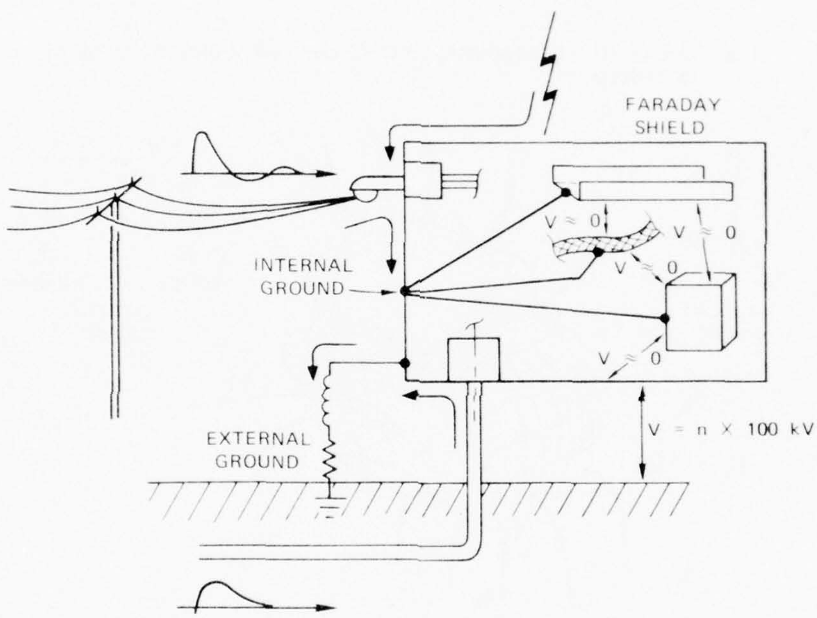


FIGURE 3 INTERNAL GROUND SYSTEM FOR EQUIPOTENTIAL REGION

The essence of an effective shielding and grounding philosophy has thus been developed. The shield is used to control internal potential differences of external origin, and grounding is used to control internal potential differences of internal origin.

III SHIELDING AND GROUNDING TOPOLOGY

The shields discussed above were assumed to be completely closed. As was remarked in the introduction, however, we must supply power to and communicate with the equipment inside the shield. For shielded buildings we must also provide openings for ventillation and for entrance and egress, as well as plumbing for water, sewage, heat or fuel, and other accouterments. Each of these openings and penetrating conductors represents a compromise of the shield; as a result a single shield and internal grounding

system is often inadequate to provide the 100 dB or more of interference reduction required by electronic circuits.

To achieve a greater degree of interference reduction, additional shields with their internal grounding systems may be used. One can thus envision a set of nested shields such as is illustrated schematically in Figure 4. The set of nested shields partitions the space about the elec-

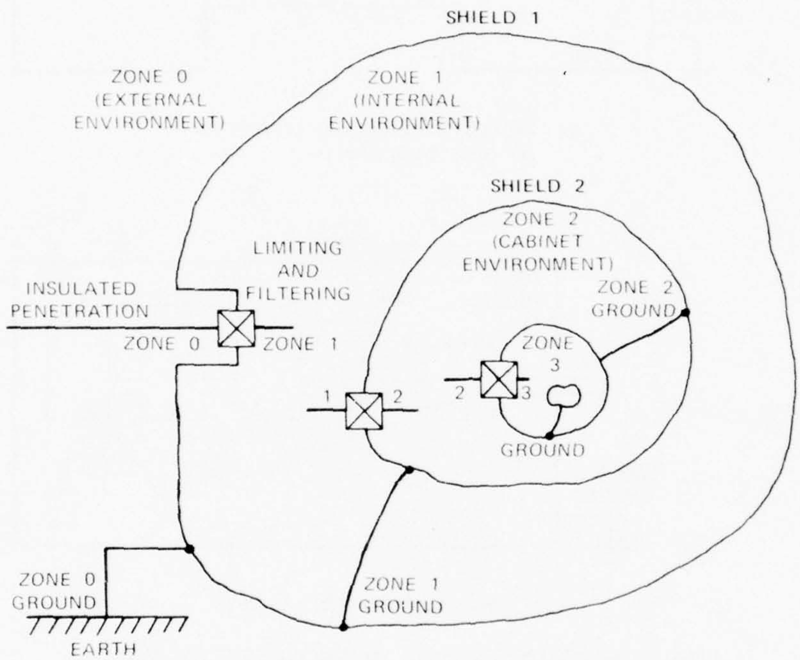
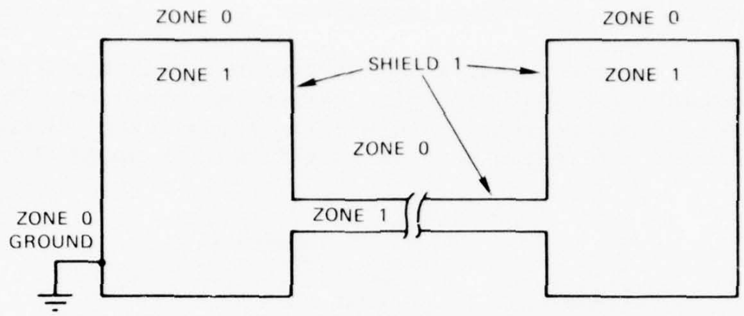


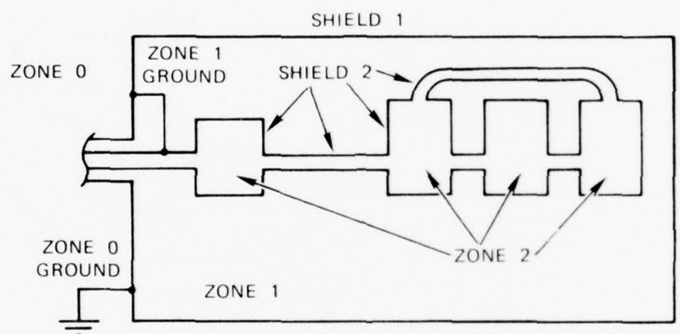
FIGURE 4 SHIELDING AND GROUNDING ZONES IN A COMPLEX FACILITY

tronic equipment into environmental zones.[2-4] Within each zone, the potential differences produced by sources in the zone are controlled by connecting all metal in the zone, including the shield enclosing the next inward zone, to the inside surface of the shield. For example, all metal in Zone 1 of Figure 4, including shield 2, is connected to the inside of shield 1; and all metal in Zone 2, including shield 3, is connected to the inside of shield 2.

Shielded regions at any level may be irregular in shape or they may be interconnected as illustrated in Figure 5. Topologically, the two shielded buildings in Figure 5(a), interconnected with a shielded cable, form one continuous shielded region. Similarly, the equipment cabinets in Figure 5(b), together with their shielded interconnecting cables or ducts, form a contiguous Zone 2 region. Also illustrated in Figure 5(b) is the use of doubly shielded cable to extend the Zone 2 region "outside" the building yet topologically inside two levels of shielding.



(a) SHIELDED BUILDINGS CONNECTED BY SHIELDED CABLE

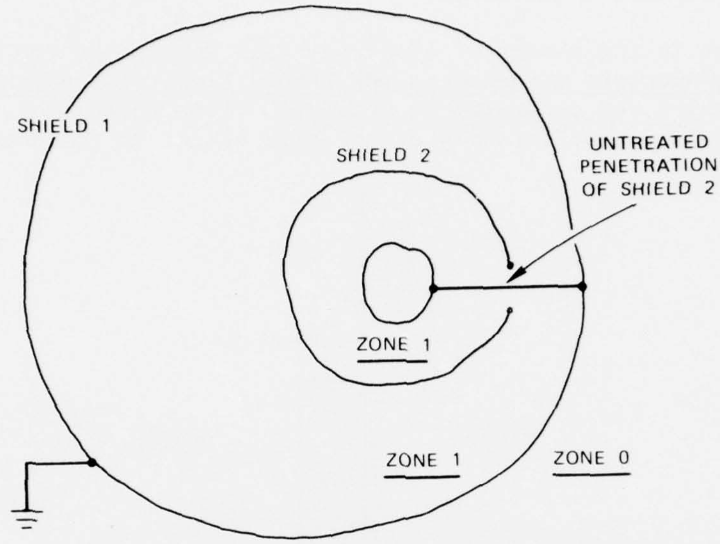


(b) INTERCONNECTED CABINETS

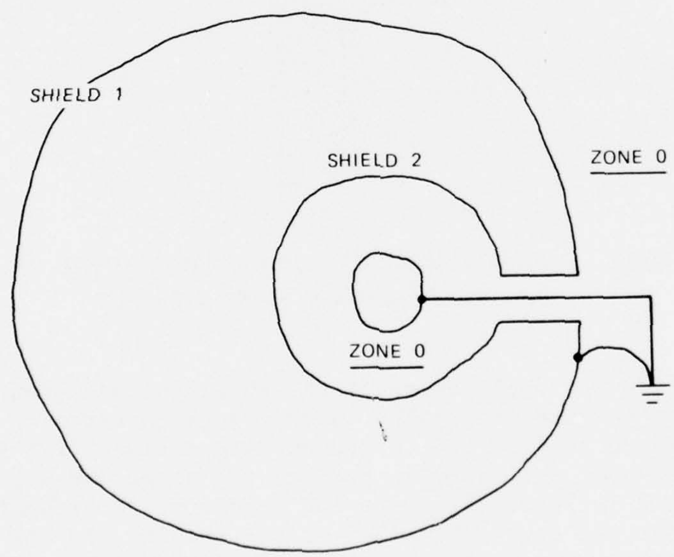
FIGURE 5 TOPOLOGY OF INTERCONNECTED REGIONS

It is useful to examine some violations of the shielding and grounding system. In Figure 6(a), components inside shield 2 have been grounded to shield 1 through an opening in shield 2. Therefore, topologically, shield 2 does not exist (i.e., it is not effective) because the grounding conductor carries the Zone 1 environment into the region enclosed by shield 2. Figure 6(b) illustrates a more serious violation because both shield 1 and shield 2 have been made to vanish by the penetrating grounding conductor. Topologically, shield 1 and shield 2 form only one shield, but this shield encloses only the region between the shields--it excludes the region inside shield 2!

These examples illustrate an important rule of effective shielding and grounding practice: Topologically, grounding conductors should never penetrate *shield* surfaces.



(a) COMPROMISE OF SHIELD 2 BY UNTREATED PENETRATION



(b) COMPROMISE OF BOTH OUTER SHIELDS BY EXTERNAL GROUND CONNECTIONS

FIGURE 6 COMMON VIOLATIONS OF SHIELDING AND GROUNDING TOPOLOGY

IV SOME IMPORTANT COROLLARIES

Inherent in the theory of electrodynamic shields is the fact that current in conductors attached to the shield flows predominantly on the surface to which the conductor is attached. This phenomenon, illustrated in Figure 7, is a manifestation of the skin effect in conductors. It is

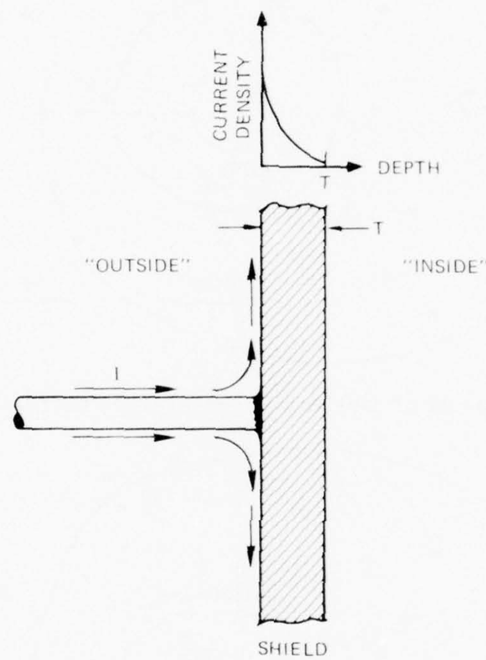


FIGURE 7 CONFINEMENT OF CONDUCTOR CURRENT TO "OUTSIDE" SURFACE BY SKIN EFFECT

very important in the application of the shielding and grounding topology developed above because it permits interference currents on conductors outside the shield to be diverted to the outside surface of the shield. Notice the difference, for example, between the situation depicted in Figure 7 and that shown in Figure 8, where the conductor is brought through the shield and connected to the "inside" of the shield. In the latter example, the conductor current flows to the "inside" surface, where it is again confined by skin effect.

Several examples of the correct application of this principle are given in Figure 9 along with some common violations of the shield. Note that each of the violations permits the harsh currents on the outside conductors to flow into the protected zone inside the shield. It should be observed that filters and surge arresters behave the same as any other connection of a penetration to the shield; that is, they divert harsh interference currents to the outside surface of the shield, thereby

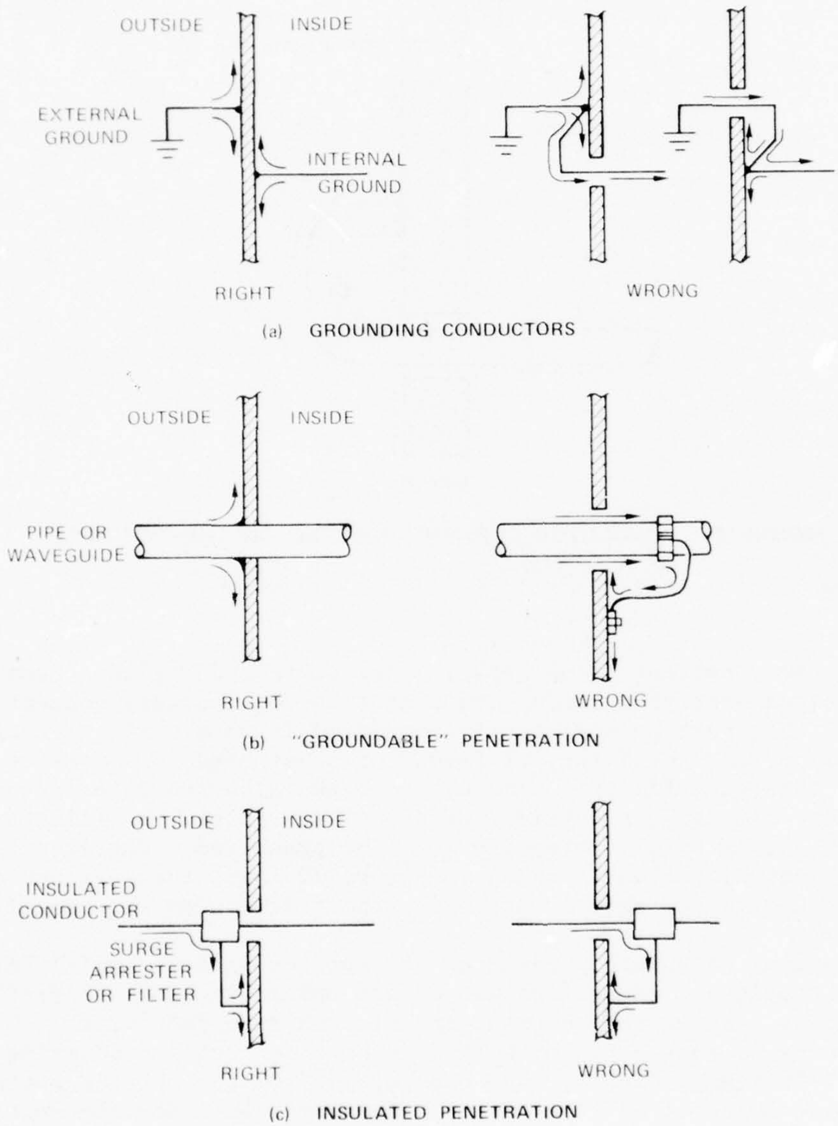


FIGURE 9 CONNECTIONS THAT PRESERVE SHIELDING INTEGRITY (right) AND COMPROMISE THE SHIELD (wrong)

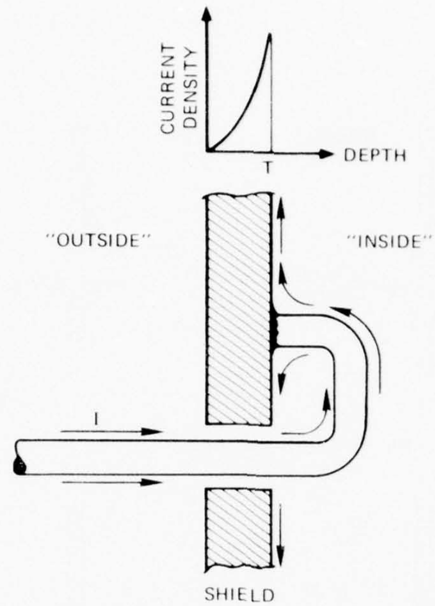


FIGURE 8 CONDUCTOR CURRENT INJECTED ON THE "INSIDE" OF A SHIELD

preventing these currents from entering the protected region. Because power and signal-carrying conductors cannot be continuously connected to the shield, they must be momentarily connected (when a certain threshold is exceeded) or connected only at frequencies not used for power or signals (i.e. through a filter). In any case, the diverted interference currents must flow to the outside surface of the shield, as illustrated in Figure 9(c), if shield integrity is to be preserved. The importance of this current diversion is shown in Figure 10 where the currents on the penetration inside the shield with and without diversion are compared.

Confinement of shield current to the surface is also useful in tracing shield topology. Identification of the shield topology is facilitated if it is assumed that current injected on a surface of the shield must flow only on that surface as it does on a perfectly conducting shield (i.e., that it cannot flow through the shield from the outside surface to the inside surface, or vice versa). One may then trace the continuous surface in the vicinity of peculiar shapes, such as those in Figure 11, to identify the shield topology. Shading (as in Figure 11) or coloring is sometimes useful when the physical geometry of the shield is complicated.

A second corollary of shielding theory is that fields cannot diffuse through shields that carry no current. The electric and magnetic fields parallel to the shield surface are both related to the current density in the shield through the intrinsic impedance of the shield material, and

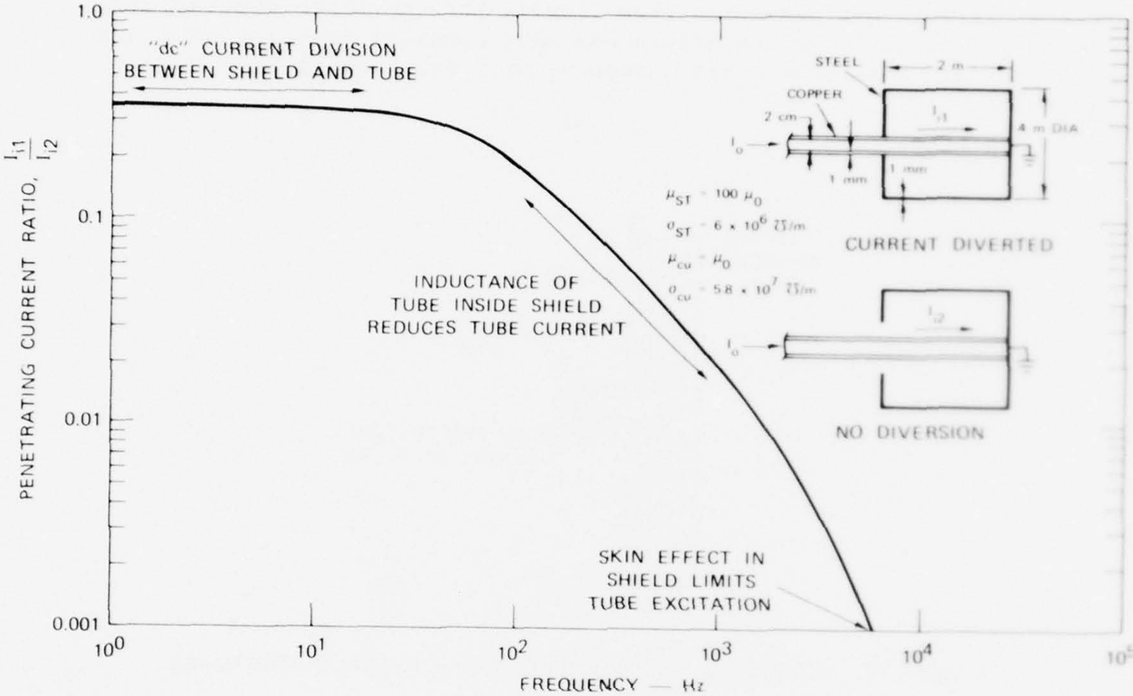


FIGURE 10 RATIO OF CURRENT PENETRATING SHIELD WALL (I_{i1}) TO CURRENT CONDUCTED THROUGH WALL (I_{i2})

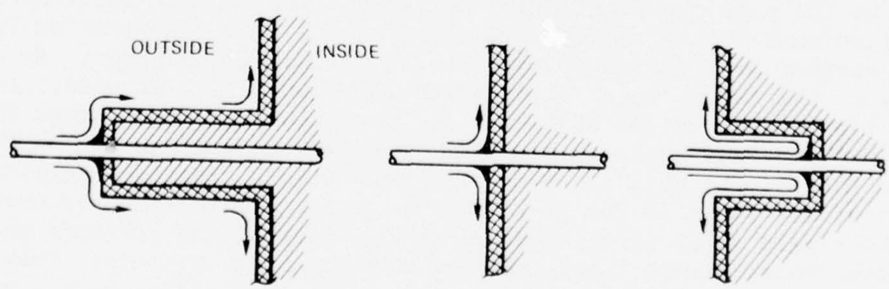


FIGURE 11 TOPOLOGICALLY IDENTICAL SHIELD PENETRATIONS

when the current density is zero, both of these fields are also zero. Therefore, the performance of the shield can be enhanced if large interference currents are prevented from flowing through large areas of the shield--particularly if the shield has many openings (e.g., a mesh or a metal building with many doors, windows, or poorly bonded joints--see Figure 12).

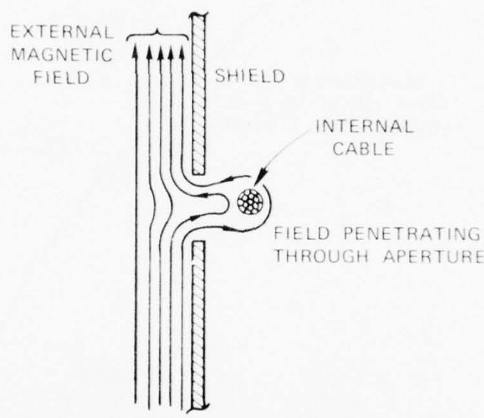
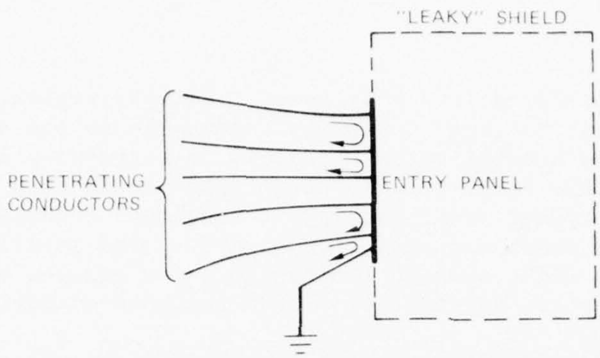
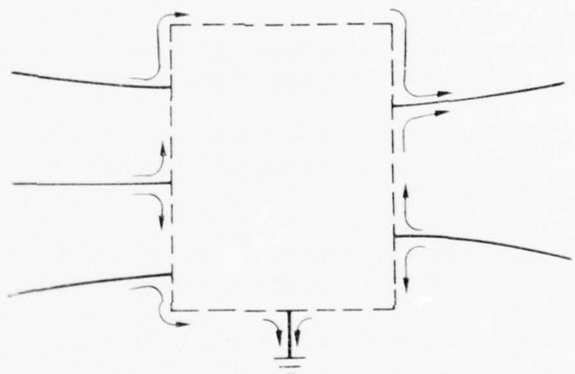


FIGURE 12 MAGNETIC FIELD PENETRATION OF SMALL APERTURES

Implementation of this principle has led to the concept of a single entry panel through which all penetrating conductors enter the shield at one small, controlled area. Figure 13(a) illustrates the entry panel with all penetrating conductors and the external grounding conductor congregated at one face of the shield. Current flowing over the shield is small because there is no exit path on the opposite face--the shield is an open-circuit to the combined penetration currents. The current entering on one penetration must either be reflected back on the same conductor or leave through another penetration or through the grounding conductor. By contrast, when the random entry illustrated in Figure 13(b) is used, heavy current flowing toward the shield on one conductor may flow across the shield, exciting any leaks in its path, and exit on a conductor on the opposite face of the shield. Hence the random entry approach permits excitation of any flaws in the shield by the external interference currents, while the single entry panel approach concentrates these currents on the entry panel where almost flawless shielding can be maintained. Conversely, if the single entry panel is used, poorer quality shielding on the remainder of the shield can often be tolerated.



(a) SINGLE ENTRY PANEL



(b) RANDOM ENTRY

FIGURE 13 PENETRATION CURRENT PATHS ON SHIELDS

V APPLICATION TO SYSTEMS

A set of nested shields, such as that shown schematically in Figure 4, often occurs in the course of constructing the facility and the electronic equipment. For example, shield 1 of Figure 4 might be the building or equipment shelter (van); shield 2 would then be the metal equipment cabinets or housing; and shield 3 would be specially shielded circuits or components within the equipment cabinet. (Shield 3 would normally be provided by the equipment manufacturer to provide extra protection for very sensitive, or very small signal, circuits and components.) Outside shield 1 is the harsh external environment described earlier.

Between shield 1 and shield 2 is the building or room environment. This region, labeled Zone 1 in Figure 4, normally contains electric power circuits operating at service voltages of 120/240 V, 120/208 V 3-phase, etc., as well as the normal transients associated with switching and

regulating the equipment operated from this power. In this region, it is desirable to limit transient voltages to levels comparable to the electric power voltages (i.e., a few hundred volts) to avoid overstressing low-voltage insulation inside the facility. In this region it is also important to interconnect all exposed metal (equipment housings, conduits, and other structures) to avoid shock and explosion hazards. The interference environment in this region might thus be limited to a few amperes or a few hundred volts on conductors and to fields of a few hundred volts/meter.

Inside shield 2 (the equipment cabinets) is the small-signal region called Zone 2 in Figure 4. This region contains the small-signal electronic circuits that are subject to malfunction at interference levels of a few volts or a few tens of milliamperes. Therefore, the peak transient interference levels on conductors entering these circuits must be smaller than those values if the circuits are to operate reliably.

When the primary and secondary shielding surfaces have been selected, it is important to examine the topology of these surfaces to

1. determine that they are topologically two separate shields rather than one with a reentrant region as in Figure 6(b) .

2. identify all penetrations and apertures that will be necessary to accommodate the system.

In the context of the second purpose, the function of the penetrating conductor (i.e., whether it is for electrical, mechanical, or hydraulic use) is immaterial to its ability to violate the shield; any conductor--even a grounding conductor--that penetrates the shield compromises the integrity of the shield.

Penetration treatments such as those illustrated in Figure 9 should be considered for each penetration of the primary and secondary shields. Because of the extremely high voltages possible on external conductors such as power lines and communication cables, high-current surge arresters are usually necessary for insulated conductors penetrating the primary shield. At the secondary shield (e.g., the equipment cabinet), a variety of interference-rejection devices may be used. Some of these may be provided as a normal functional part of the equipment. For example, dc power supplies may serve to isolate the electronic circuit from the interference on ac power conductors, and dc-to-dc converters can perform a similar role when the primary power is dc. These and some other secondary-shield penetration treatments are illustrated in Figure 14. Cable shields and other "groundable" conductors may be treated at the secondary shield in much the same manner as they are treated at the primary shield--see Figure 9(a) and (b).

Of particular interest are the ac power entry and grounding provisions. Topologically proper methods of treating these penetrations are shown in Figure 15. Figure 15(a) illustrates the topology of the primary shield at

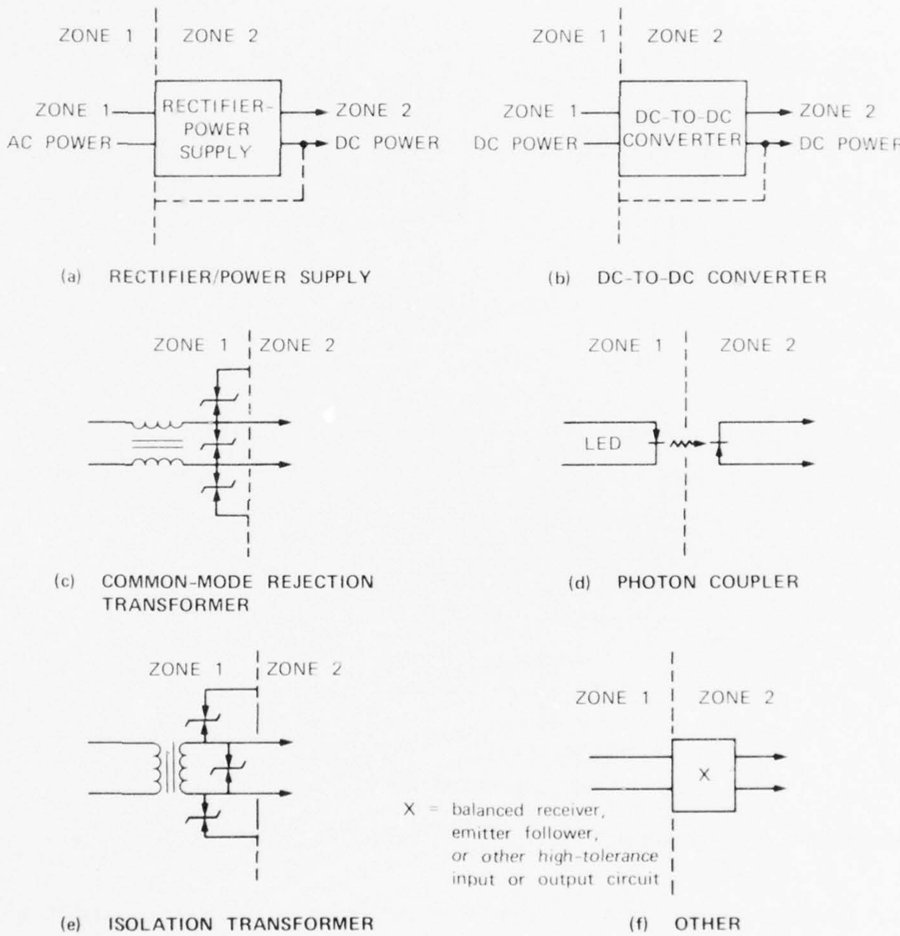
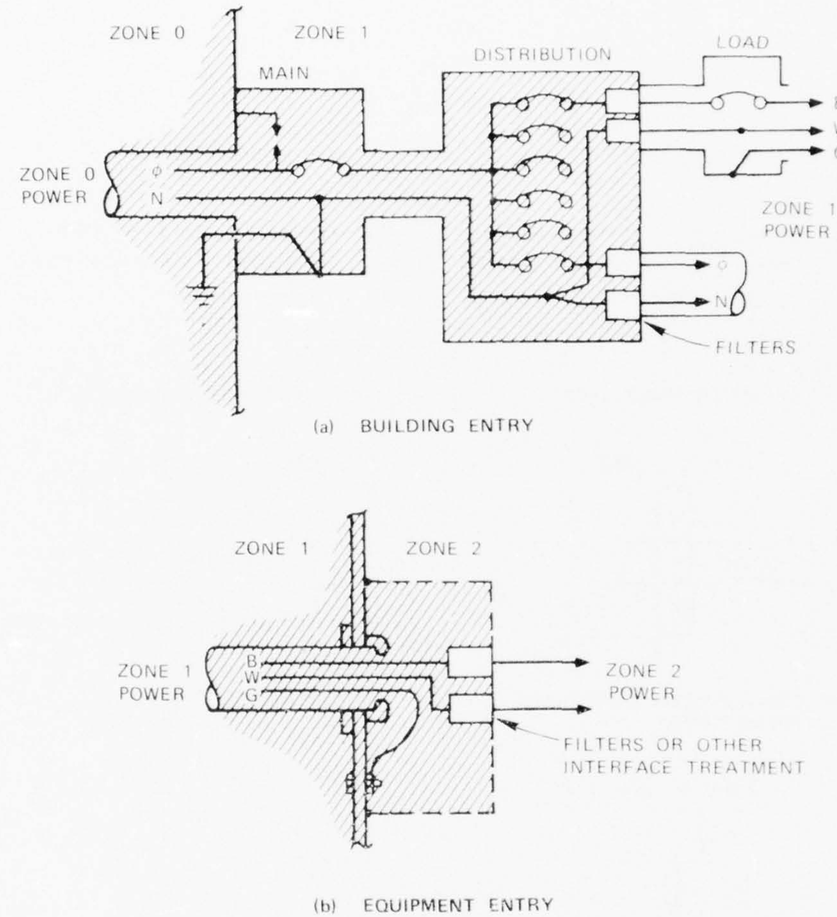


FIGURE 14 TREATMENTS FOR SECONDARY SHIELD PENETRATIONS



(a) BUILDING ENTRY

(b) EQUIPMENT ENTRY

FIGURE 15 AC POWER PENETRATIONS AND GROUNDING CONDUCTORS

the service entrance. For this installation the main disconnect and distribution panel are outside the shield since the power conductors are not filtered until they leave the distribution panel. Two options for the grounding conductor are shown; in the upper right, a Zone 1 electrical ground (green wire) is derived in a load center serving the electronic equipment, while in the lower right, the conduit serves as the grounding conductor. In Figure 15(b) the two options for the grounding conductor (conduit or green wire) are also shown, although they are combined in one picture (both are not needed). Note that the preferred equipment entry utilizes a junction box or back-plane region to shield the interior of the cabinet from the unfiltered power conductors and green wire connection.

VI CONCLUSIONS

The topological approach to shielding and grounding is a rational and systematic method of providing the high degree of isolation required between external conductors exposed to lightning or other harsh environments and small-signal circuits susceptible to transients of a few volts.

It is clear that primary protection from externally-generated interference is obtained from shielding; grounding is not a good deterrent to this interference. In fact, improper grounding procedures (e.g., Figure 6) may aggravate the problem rather than solve it. Although the diversion of penetrating conductor currents to a shield (see Figure 9) is often considered an aspect of grounding, the topological approach shows that it is in fact a method of preserving the integrity of the shield.

Topologically, grounding has no effect on externally-generated interference. Grounding serves only to equalize the potentials of otherwise insulated metal parts within a shield. In so doing, it helps control spurious potentials generated by sources inside the shielded region.

Because the topology of shielding and grounding dictates that grounding conductors should not penetrate shield surfaces, some of the problems encountered in past grounding practices can now be understood. The circuit upset and damage problems associated with the common practice of connecting small-signal ground (Zone 2) to the building electrical ground electrode (Zone 0) are readily understood from the topological picture in Figure 9(b). According to this picture, any natural shielding that might have been provided by the building (shield 1) or equipment cabinet (shield 2) has been circumvented by the grounding conductor, thereby exposing the small-signal circuits to the harsh outside environment.

It is also interesting that attempts to alleviate this problem have often been concentrated on reducing the grounding electrode impedance--thereby reducing the n-hundred kV in Figure 1--rather than on improving the integrity of the shields by eliminating the offending grounding conductor. An important advantage of the shielding and grounding philosophy enunciated here is that system performance is completely independent of the grounding electrode impedance. The properties of the grounding electrode can therefore be left to the discretion of power and communication utilities.

It is noteworthy that the single-entry concept alleviates the requirement for a high-quality overall shield if the principal source of interference is large currents on outside conductors such as power lines and communication cables. By diverting these currents at the entry panel rather than allowing them to flow through the shield, a moderate-quality shield (e.g., structural steel or reinforcing steel) may suffice for many installations. If high intensity interference fields, as well as conductor currents, prevail as in the nuclear EMP environment, a high-quality shield may be required.

Finally, implementation of the shielding and grounding approach described in this paper does not entail costly new equipment and processes.

On the contrary, it may eliminate some of the costly grounding electrode installations and extravagent use of heavy copper bars and cables frequently specified in the name of "good grounding." The essence of the approach and its principal advantage is that it provides a rational method of achieving the maximum interference protection from the structural metal, housings, etc., that would usually be provided even if interference were not a consideration. The principal effort required to implement the approach is, therefore, in configuration control. Thus the approach promises improved circuit protection, hence improved system reliability and reduced maintenance costs, as well as potentially lower initial costs.

REFERENCES

1. E. F. Vance, "Coupling to Cables," DNA 2114, Chapter 11 (revised), Defense Nuclear Agency, Washington, D.C. (December 1974).

2. F. M. Teshe, et al, "Internal Interaction Analysis: Topological Concepts and Needed Model Improvements," Interaction Note 248, Air Force Weapons Laboratory, Kirtland AFB, New Mexico (July 1975).

3. C. E. Baum, "How to Think About EMP," Proceedings of the 1974 FULMEN Meeting, Air Force Weapons Laboratory, Kirtland AFB, New Mexico (April 1974).

4. C. E. Baum, "The Role of Scattering Theory in Electromagnetic Interference Problems," P.L.E. Uslenghi, (Editor) Electromagnetic Scattering, Academic Press (to be published).

AN INVESTIGATION INTO THE NOISE INTERFERENCE PROBLEMS AT LOGAN AIRPORT, BOSTON

(INVESTIGATION OF SEVERE NOISE PROBLEMS AT AIR TRAFFIC CONTROL TOWER LOCATIONS)

by

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ABSTRACT

A severe noise problem exists at many air traffic control tower locations in the VHF receivers during certain severe weather conditions. The problem has briefly been investigated at Boston Logan Airport and has been found to be most likely related to corona discharge from air terminals close to the receiving antennas. The effect of the charge that can accumulate on the radome has not yet been well identified. The charge from raindrops transferred to the antennas seems unlikely as a noise source, but could not entirely be ruled out. Elimination techniques using static dischargers at some ATCT locations have been analyzed and are criticized. Suggestions for possible corrective procedures include relocation of the air terminals or placing corona balls over the tips of the lightning rods. The latter modification will also enhance the lightning protection capabilities.

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1.0 NOISE INTERFERENCE PROBLEM AREAS

1.1. Noise Problem

A severe noise problem exists at numerous Air Traffic Control Tower (ATCT) locations in the VHF/UHF receivers during certain rainstorms, snowstorms or thunderstorms. The noise is often continuous and is characterized by a high pitched hissing or screaming sound. It can last for many tens of minutes and be so intense that the controllers are unable to receive communications from aircraft for a considerable period.

A number of airports are investigating the problem while other airports have carried out certain questionable solutions to the problem. Static dischargers have been purchased to alleviate the radio interference, but these dischargers are considered by us to play no part whatsoever in correcting the problem. The Midway Tower in Chicago purchased ten such dischargers in the Fall of 1975 and since that time, the devices have been installed at the following airports:

Midway	Bismark	Atlanta
Flint	Pueblo	Louisville
Youngstown	Minot	Stanford
Indianapolis	Colorado Springs	Tampa
Darwin	Denver-Arapaho	Parkesburg
Rhinelander		
Fairmont		

There are undoubtedly many more facilities in these and other regions with similar problems, and it is unfortunate that much effort and funding is being expended by different people in order to attempt to alleviate the problem. A single investigation should be performed that would result in recommendations to all ATCT locations which, when carried out, would eliminate this potential hazard.

Electrical breakthrough on the VHF receivers has occurred at various times at Logan International Airport, Boston, and to illustrate the problem, excerpts from an internal memorandum are reproduced.

"On Sunday, August 1, at 1500 Z, the tower reported electrical breakthrough on main 119.1RX, which is located on the 21st floor of the tower with its antenna above the cab. They switched to standby 119.1RX, which is presently in the equipment room of the old tower building with its antenna on the old tower building roof.

The weather conditions at this time were misty and overcast, with electrical storm cells in a line approximately 4 miles wide and 25 miles long stretching north and south. This line was located 10 miles west of the airport moving in an easterly direction.

During the period 1500 Z to 1529 Z, both receivers were monitored at the jack panel on the 6th floor. The ratio of short bursts of electrical static breakthrough on the main 119.1RX to the standby 119.1RX was approximately 3:1.

The electrical storm cell reached the airport at 1530 Z. Electrical breakthrough became more frequent and longer in duration on the main 119.1RX. The standby 119.1RX continued to have short electrical breakthrough similar to when the storm was 10 miles west of the airport.

At 1531Z, the main 119.1RX seemed to go into oscillations which lasted nearly 1 minute. The standby 119.1RX continued to have short burst of electrical breakthrough. Rain was very heavy at this time.

During 1532Z to 1533Z, the main 119.1RX went into oscillations again (caused by electrical discharge). This time the RF gain was decreased to eliminate the oscillation. At this gain setting, 5µV from a signal generator (HP-608D) was necessary to break the squelch. The receiver was then returned to 2µV squelch break.

The electrical storm had dissipated some over Boston, and by 1540Z it was approximately 2 to 4 miles at sea. Our main 119.1RX during the period 1532Z to 1540Z returned to normal operation, with electrical breakthrough decreasing in duration. The standby 119.1RX also decreased in electrical breakthrough during this period."

1.2 Logan Airport Layout

The new control tower at Logan Airport, shown in Figure 1, is approximately 301 feet high. The receiving antennas for aircraft communications are on top of the tower and spaced around a walkway which circumscribes a radome. A lightning rod is placed on top of the radome and other lightning rods are spaced around the walkway parapet.

Figure 1. The air traffic control tower at Boston's Logan Airport.

The layout of the antennas and lightning rods is shown in Figure 2. Figures 3a-3c show the approximate positions of some of the antennas relative to the air terminals and the approximate distances to the probable corona source at the tip of the lightning rod. Antenna mount number six shows a VHF antenna only 18 1/2 inches from a corona source, and other antennas are spaced not too much further away from other lightning rods. The nearest UHF antenna is some 35 inches away.

The parapet, radome framework and air terminals appear to be excellently grounded with all lines being inter-connected before the grounding system is reached. It was, however, difficult to decide if the coaxial lines from the antennas were grounded at both ends or just at one end.

1.3 Reduction of the Noise Problem by Installation of Static Dischargers

In September of 1976 the Midway Tower, Chicago successfully reduced their corona problem with the installation of static dischargers on the lightning rods. Other locations installed similar devices and the overall results were usually significant. Chicago indicate about an 80-90% reduction in the occasions of corona noise, although the devices gave no improvement at Fairmont. Logan Airport installed them in mid August which seemed to improve the situation, since during some local storms in the following month no noise problems existed. However, noise was monitored again during snowstorm and high wind conditions during the winter.

The static dischargers used at most of these facilities are made by Dayton Aircraft Products of Fort Lauderdale, whose literature appears in Appendix A. These static dischargers are primarily for aircraft use where they offer a controlled path to bleed off the accumulated charge on an aircraft. They attenuate the resultant broadband radio frequency noise by approximately 50db as compared to a discharge from the tip of a wing without dischargers installed, because more frequent low amplitude dis-

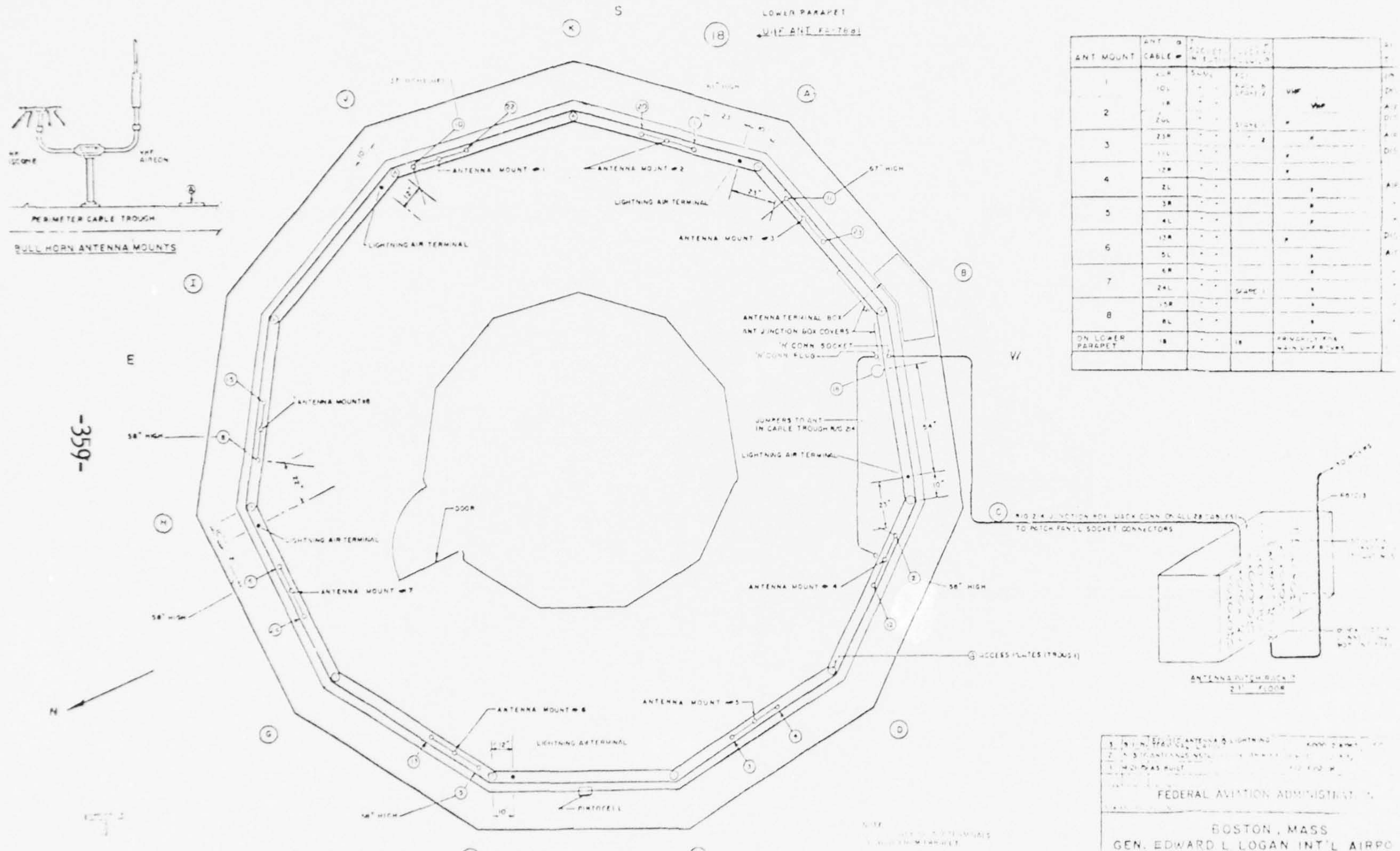


Figure 2. Logan International Airport Air Traffic Control Tower, Roof Antenna Layout

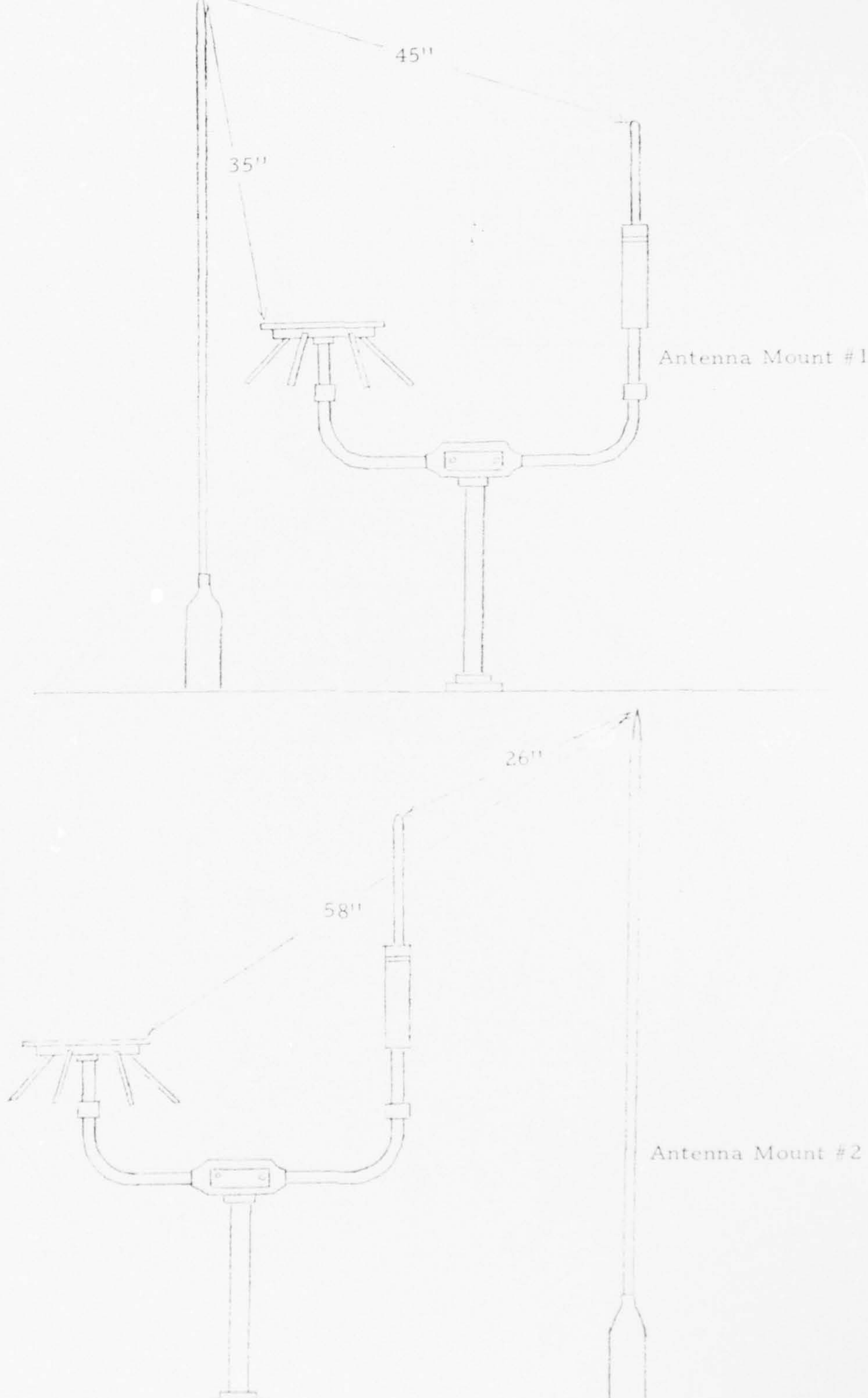


Figure 3a. Configurations of Antenna Mounts and Lightning Rods

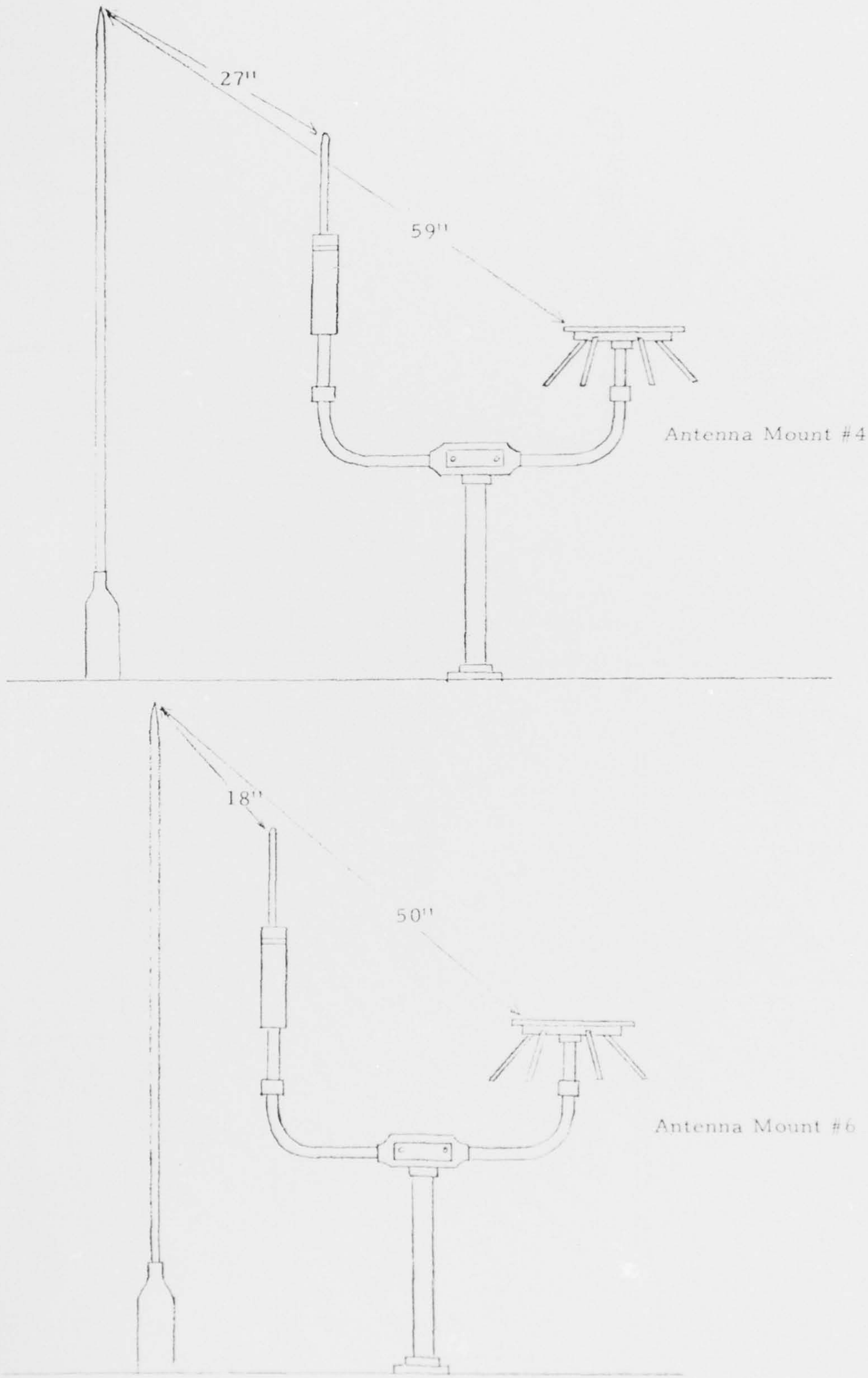


Figure 3b. Configurations of Antenna Mounts and Lightning Rods

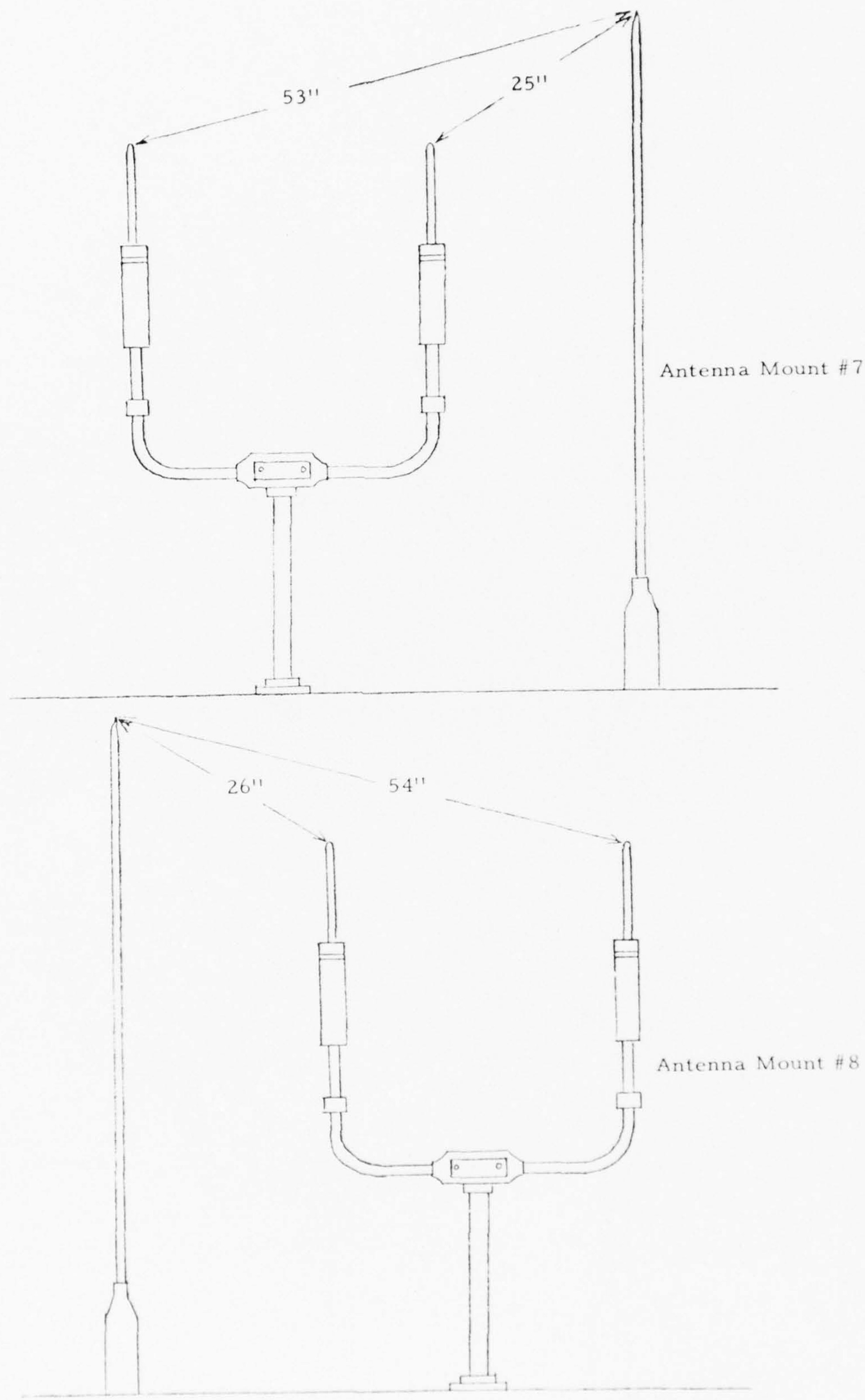


Figure 3c. Configurations of Antenna Mounts and Lightning Rods

charge pulses will occur with the small points of the dischargers than with larger points. In effect, they attempt to bring the potential of the body on which they stand to the potential of their surroundings using the principle of point-discharge over many thousands of special four micron diameter wires to reduce the noise coupling to the aircraft. Such devices no doubt work extremely well on the aircraft for which they were designed.

For the purposes of reducing the noise at ATCT locations, the static dischargers were connected to the lightning rods, as shown in Figures 4 and 5, utilizing 3/4" x 3/4" x 16" angle iron to support them. These figures show that the static discharging wires point downward, which, due to the mounting configuration of the lightning rods, is always in a region of reduced field over the surrounding area.

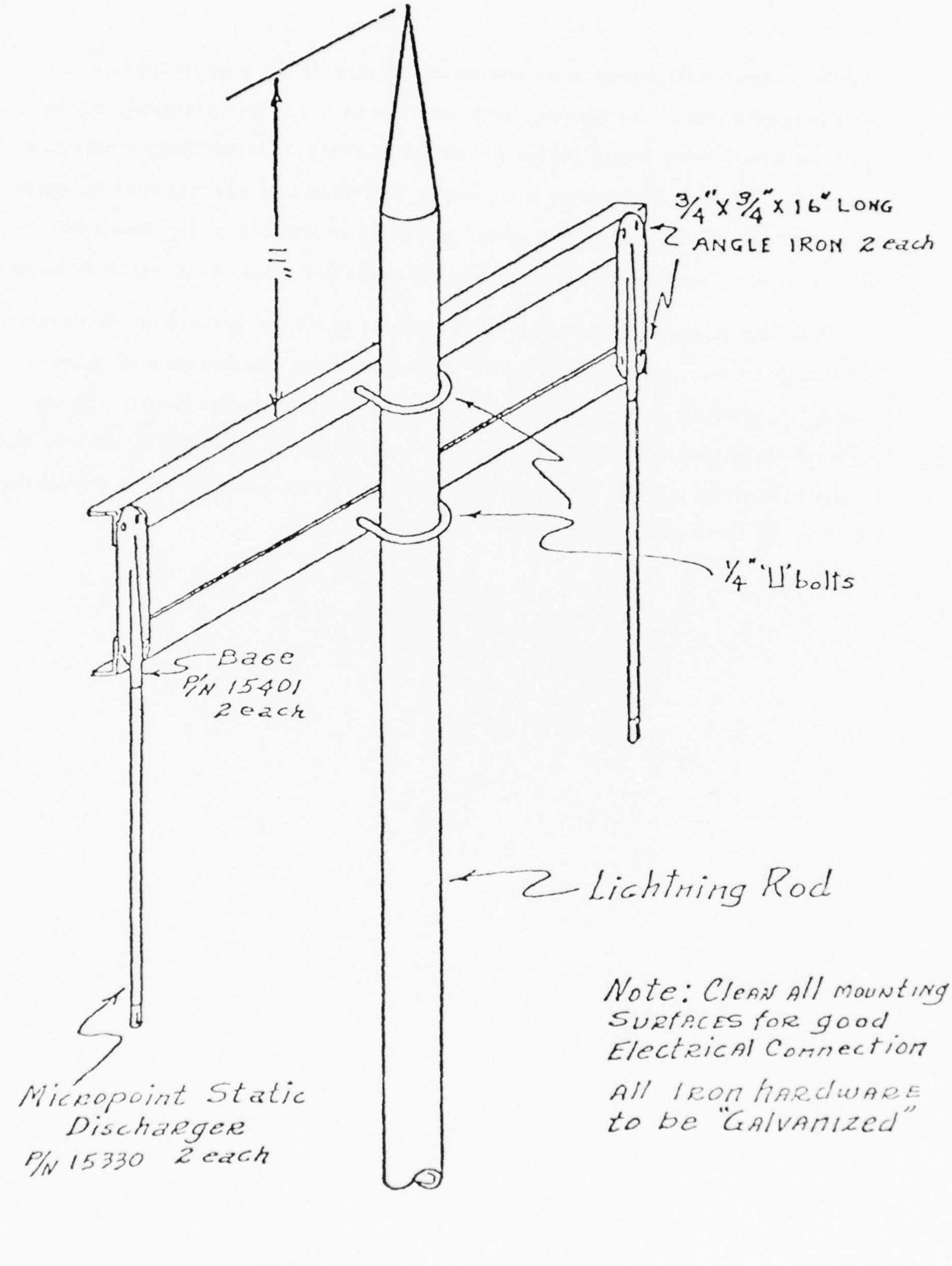


Figure 4. Installation of Static-Discharger on ATCT Lightning Rod

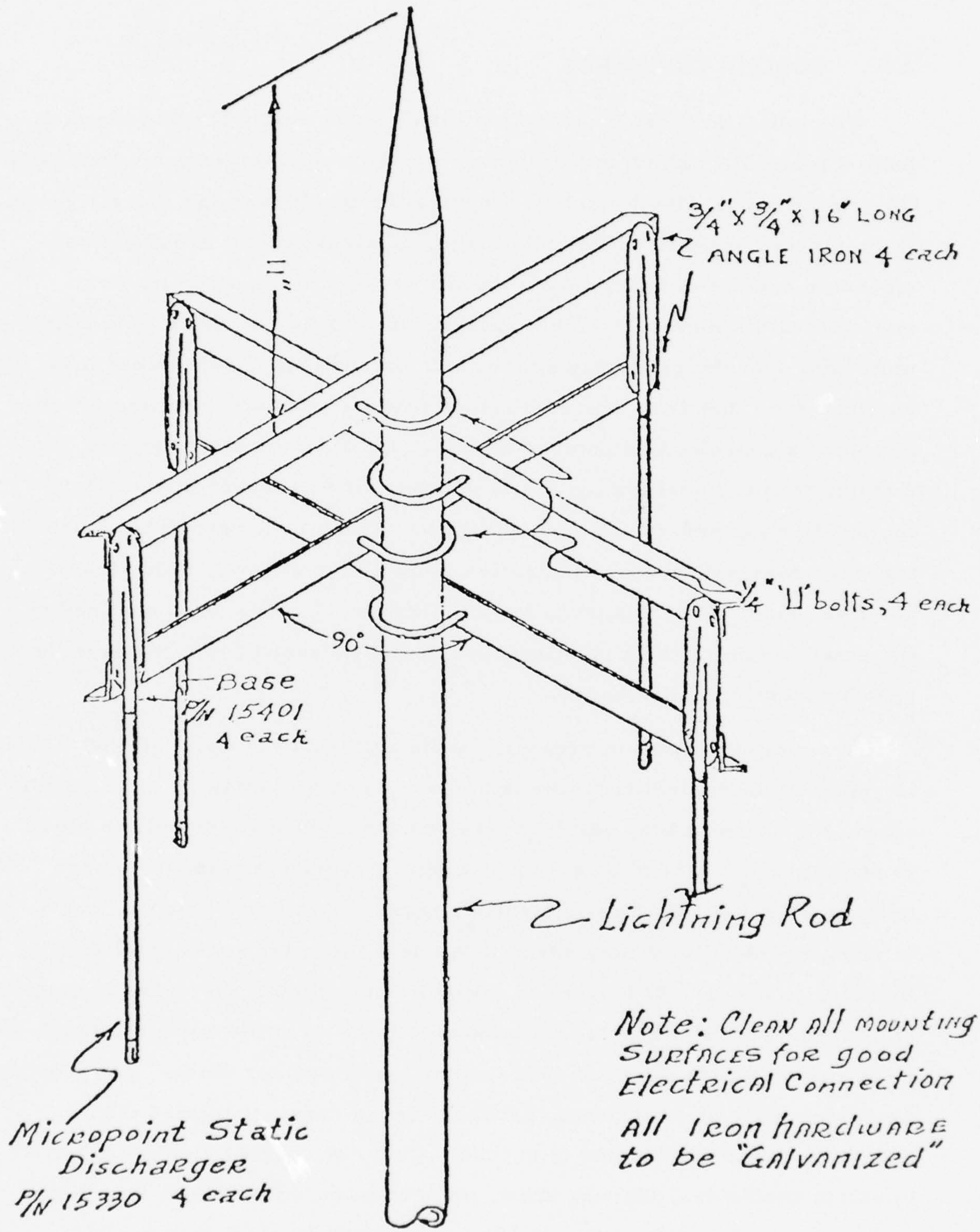


Figure 5. Installation of Static Discharger on RCAG Lightning Rod

2.0 CORONA DISCHARGE

The initial process of ionization involves the removal of an electron from a molecule, which in turn leaves a positively charged ion. Normally this electron will attach itself to a neutral molecule forming a negative ion. If the electric field is sufficiently large, an electron will acquire a considerable amount of energy from the time it was produced to its first collision with a molecule. This energy can be great enough to ionize the molecule, thereby producing a new electron and ion. The process may continue such that from one electron an avalanche process occurs which produces a considerable number of ions. Because the electrons are smaller than the positive ion it has just left, it will travel further than the positive ion before collision and gather greater energy. This means that electrons will produce ionization by collision at lower fields than positive ions. When this process of ionization by collision is confined to the small volume near a point because of the enhanced field, we have the phenomena of point discharge.

In air at atmospheric pressure, a field strength of about 30,000 V/cm is required for ionization to occur. When a charge builds up in a thundercloud, the fields nearby will increase and the highest fields will be close to sharp points. These points can therefore provide a point-discharge current when the field is sufficiently intense. Where the potential continues to rise, the conditions may reach those necessary for spark discharge or lightning to occur. At heights of several hundred feet, an isolated grounded point may cause field enhancement above its tip of sufficient magnitudes to be in corona discharge even under normal fair weather skies. This corona discharge will, at such times, probably cause currents of less than 1/4 μA to flow down the rod to ground. Under the higher fields that exist in storm conditions, blowing snow, or near to ocean breakers the corona current may approach values of 100 μA for periods of about a minute.

Significant levels of corona current can also occur on much lower structures under high field conditions. Basically corona current magnitude

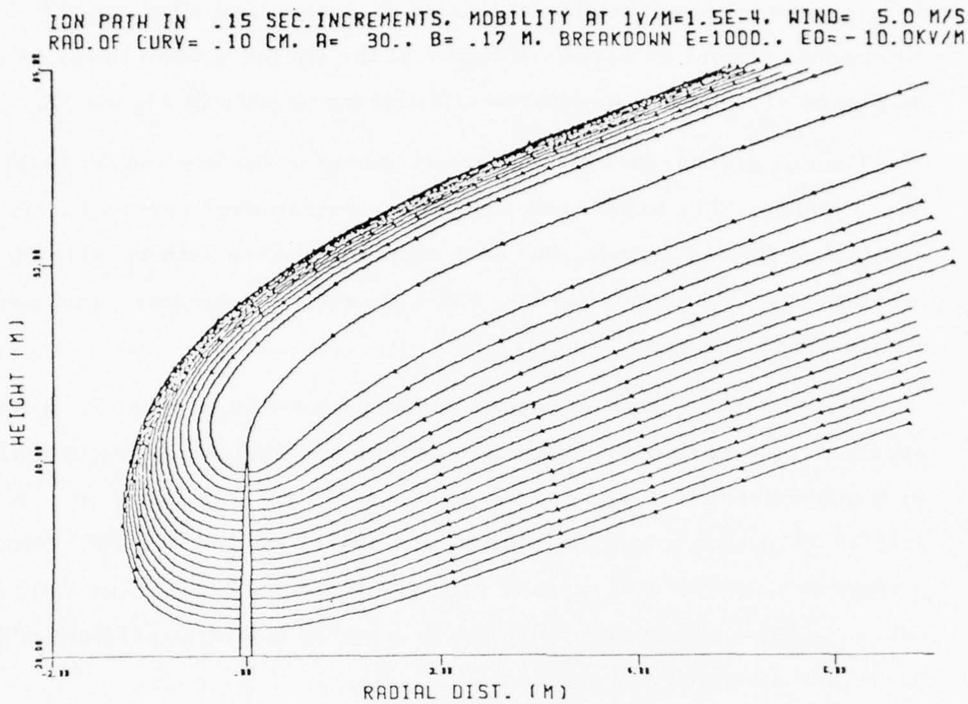
is a function of point height, radius of curvature and wind speed. The field enhancement or exposure factor at the tip for a 30 m tower is shown in Figure 11, and for structures of different heights in Figure 12.

Corona discharge will, therefore, occur in the air above elevated sharp points. The breakdown from these extremities occurs not as a continuous flow of charge, but as a series of pulses with roughly 10 nsec risetime and 200 nsec duration, and it therefore generates radio noise over a broad spectrum.

The effects of wind on corona are illustrated in Figure 6. In this approach only horizontal winds are considered neglecting any updrafts as might exist before and during thunderstorms. The last 2 m of a pointed 30 m high tower are plotted in a storm field of -10,000 V/m. Ionization along the rod surface will take place only where the field is enhanced to values greater than the breakdown potential gradient which is roughly assumed at 1 million V/m.

First, to determine the outermost boundary of a possible space charge cloud, consider the simple picture where space charge does not effect the field. Two cases for winds of about 10 and 30 knots are shown. Under effect of the field the ions move upward and out to the sides, and the wind adds an extra horizontal component to their movement, creating a sort of concentrated line charge as the ions travel around the tower. The ion speed right at the tower is very high and drops off radidly with distance.

The situation can now be considered with space charge limiting. Once corona is formed and starts moving out from the tower, its charge would reduce the field around the tower to below the breakdown potential gradient, and corona discharge would cease. Within a fraction of a second the wind would blow the charge clear of the tower, exposing it again to high fields, and ions would be formed again etc. This causes the corona currents to be given off in bursts, as first observed by Trichel[1] in 1938.



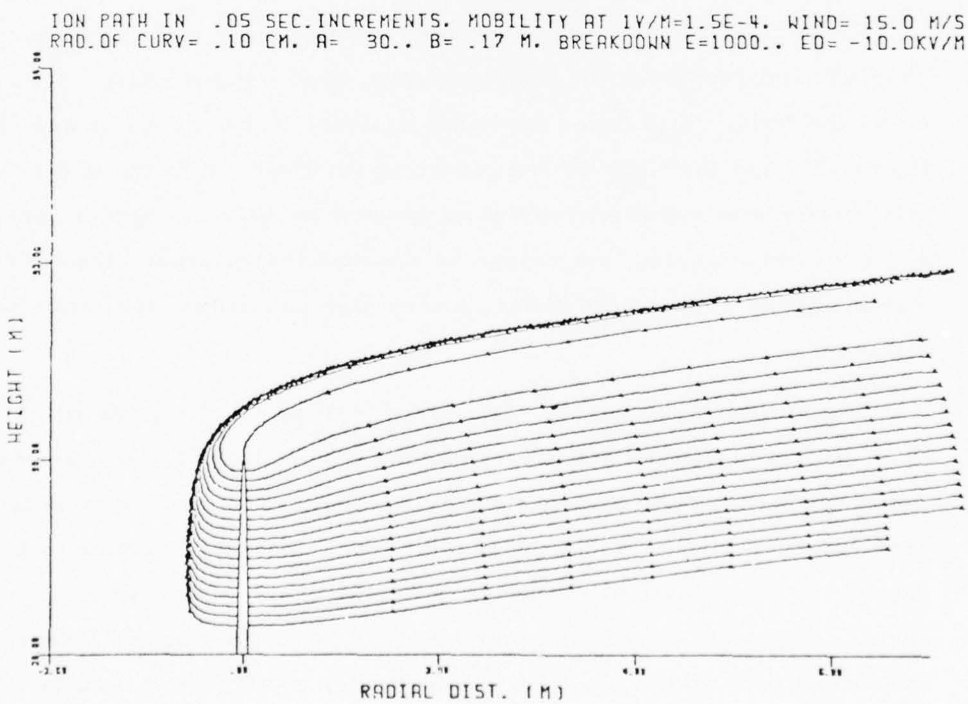


Figure 6. Ion movement under horizontal winds showing maximum boundary of ion cloud.

The magnitude of the corona current increases with rising wind speed, as shown in Figure 7, for 0 and 35 knots. In the equation relating the corona current i to the wind speed v and the point potential V, V_o is the starting potential, D/D_o is the ratio of the atmospheric density to the standard, and k the ion mobility.

$$i = 1.315\,\epsilon_o\, v\,(V - V_o)\left(\frac{D_o}{D}\right)^{.31} + 1.785\,\epsilon_o\, k\left(\frac{D_o}{D}\right) V\,(V - V_o)$$

Since the point geometry such as the radius of curvature does not enter the equation explicitly but is inherent in the coefficients and V_o, it is difficult to compute theoretical values of corona current for a particular configuration.

The degree to which the radio frequency noise generated by corona discharge couples into electronic systems is determined by the relative locations of the noise source, and the antenna via which the noise is coupled into the affected system. In addition, the coupling depends on frequency and the size of the antenna.

It can be shown that individual pulses associated with a corona discharge can be approximated by a decaying exponential with zero rise time, as follows:

$$F(t) = Ae^{-\alpha t}$$

where A is the pulse amplitude and α is the pulse decay constant. The noise spectrum produced by ν such pulses occurring each second as a function of frequency ω is given by,

$$P = A\left(\frac{\nu}{\pi}\right)^{\frac{1}{2}} \left(\omega^2 + \alpha^2\right)^{-\frac{1}{2}}$$

Figure 8 shows the relative noise-current spectral density plotted as a function of frequency indicating a rapid drop in the spectrum magnitude with increasing frequency. The effects will, therefore, be much lower at UHF than VHF.

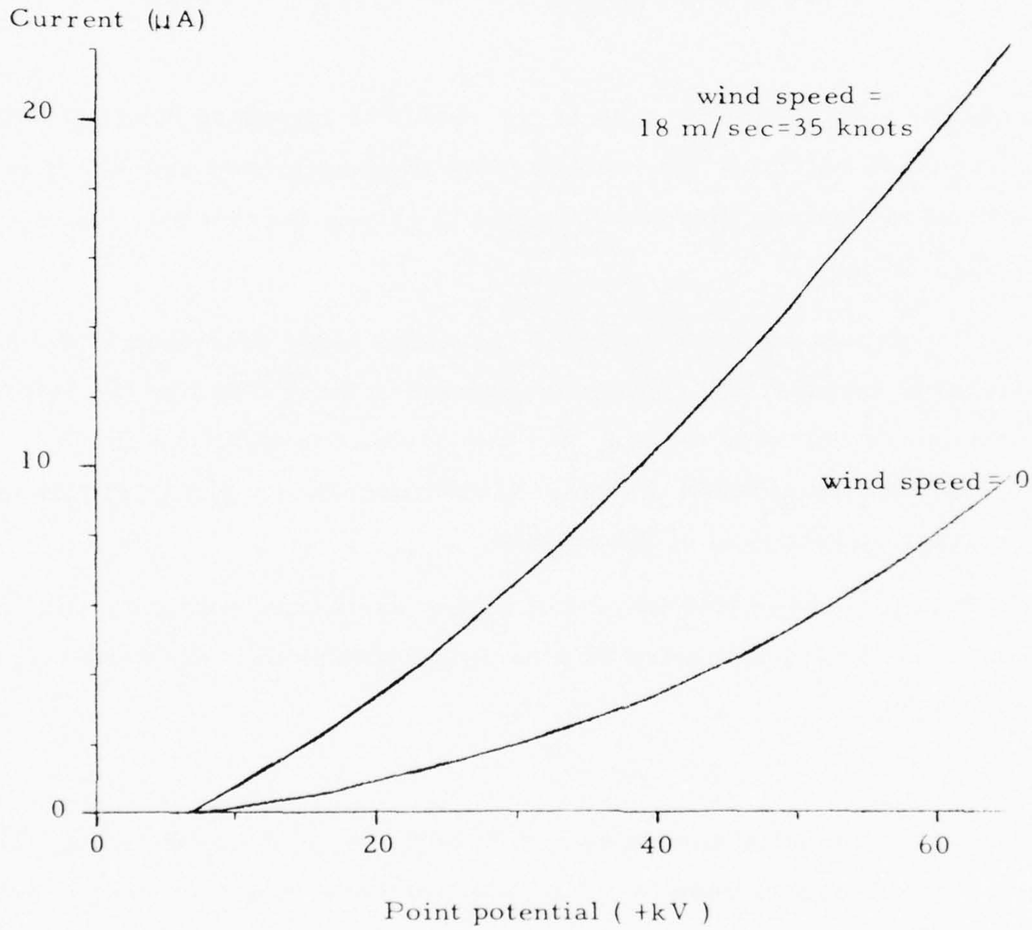


Figure 7. Corona current as a function of the point potential and wind speed. (adapted from Chapman [2])

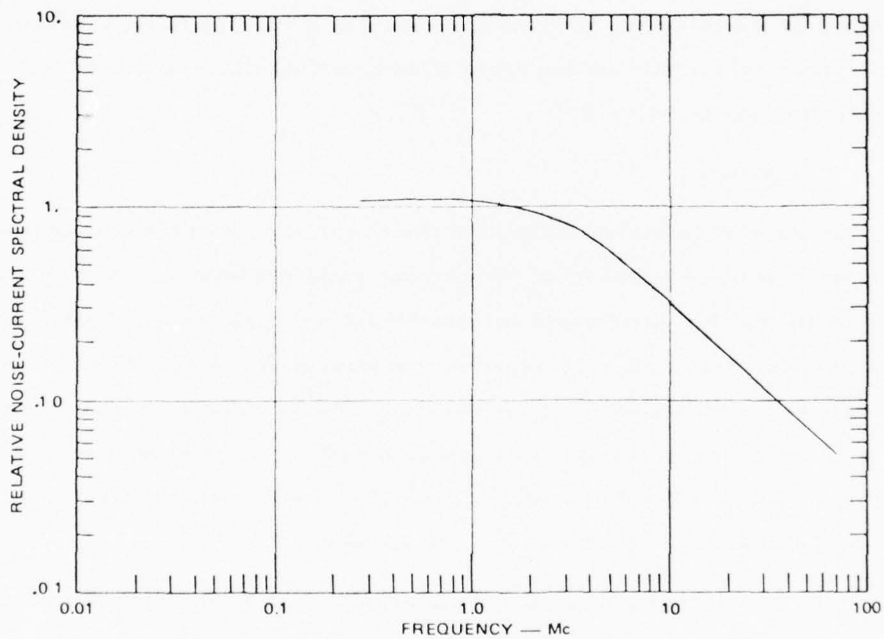


Figure 8. Corona noise spectrum characteristics.
(adapted from reference 3)

3.0 SHARP VS. BLUNT POINTS

In order to better understand the atmospheric conditions around structures of various shapes and heights, a theoretical investigation was performed of the corona currents given off from sharp and blunt points, and of the electric fields influencing the corona. Very simplified situations of static field conditions were examined, from which conclusions could be drawn about the dynamically changing situations. The results of these investigations lead to some surprising conclusions which, at the moment, are causing several questions to be asked in the scientific community on the types of points that should exist on lightning protective air terminals.

3.1 Equations

In the theoretical calculations the tower structures were approximated by prolate spheroids, which bear good resemblance to the overall shape and are convenient for mathematical treatment. A uniform ambient electric field was assumed parallel to the vertical axis of the structures, and the structures were considered to be at ground potential. For these conditions Laplace's electric field equations were solved in elliptical or prolate spheroidal coordinates as discussed in references 4 and 5, to give the potential and potential gradient.

The resulting equation for the potential as a function of the elliptical coordinate ξ with major and minor half axes a and b is,

$$\varphi = \varphi_0 + (\varphi_s - \varphi_0)\frac{\displaystyle\int_{\xi}^{\infty}\frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}}{\displaystyle\int_{0}^{\infty}\frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}} = \varphi_0 + (\varphi_s - \varphi_0)\frac{I_1}{I_2}$$

The potential at the surface $\varphi_s = 0$, because the conducting ellipsoid is grounded, and the potential at height h in the unperturbed parallel field E_0 is $\varphi_0 = -E_0 h$.

$$\varphi = -E_0 h \left(1 - \frac{I_1}{I_2}\right)$$

The vertical and horizontal components of the electric field are,

$$E_V = -\frac{\partial \varphi}{\partial h} = E_0 \left(1 - \frac{I_1}{I_2} \right) - \frac{E_0 h}{I_2} \frac{\partial \xi}{\partial h} \frac{\partial I_1}{\partial \xi}$$

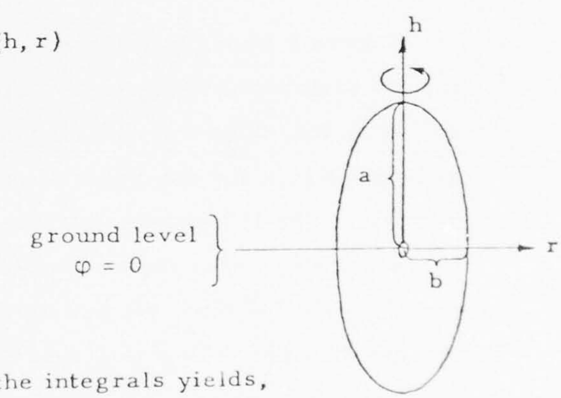
$$E_H = -\frac{\partial \varphi}{\partial r} = -\frac{E_0 h}{I_2} \frac{\partial \xi}{\partial r} \frac{\partial I_1}{\partial \xi}$$

The equation of the ellipsoid,

$$\frac{x^2}{\xi + a^2} + \frac{y^2}{\xi + b^2} + \frac{z^2}{\xi + c^2} = 1$$

is simplified for the symmetrical case of the prolate spheroid, where the semimajor axis is a, the two semiminor axes b = c, the radial coordinate is the horizontal distance from the center of the ellipsoid $r^2 = y^2 + z^2$, and the height coordinate $h = x$;

$$\frac{h^2}{\xi + a^2} + \frac{r^2}{\xi + b^2} = 1 \quad \text{and} \quad \xi = f\,(h, r)$$



The partial derivatives are,

$$\frac{\partial \xi}{\partial h} = \frac{2h\ (\xi + b^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$

$$\frac{\partial \xi}{\partial r} = \frac{2r\ (\xi + a^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$

Setting $c = a^2 - b^2$, the evaluation of the integrals yields,

$$I_1 = -\frac{2}{c^2 \sqrt{\xi + a^2}} - \frac{1}{c^3} \ln \frac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}$$

$$I_2 = -\frac{2}{ac^2} - \frac{1}{c^3} \ln \frac{a - c}{a + c}$$

$$\frac{\partial I_1}{\partial \xi} = -\frac{1}{(\xi + a^2)^{3/2} (\xi + b)^2}$$

Hence the equations for the potential φ, the vertical component E_V and the horizontal component E_H of the electric field around a conducted grounded prolate spheroid in a parallel electric field E_0 are as follows:

$$\varphi(h,r) = \varphi\left[h, \xi(h,r)\right] = -E_0 h \left(1 - \frac{\dfrac{2}{\sqrt{\xi + a^2}} + \dfrac{1}{c} \ln \dfrac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}}{\dfrac{2}{a} + \dfrac{1}{c} \ln \dfrac{a-c}{a+c}} \right)$$

$$E_V = -\frac{\varphi}{h} - \frac{2 E_0 h^2}{\left(\dfrac{2}{ac^2} + \dfrac{1}{c^3} \ln \dfrac{a-c}{a+c}\right) \cdot (\xi + a^2)^{3/2} (2\xi + a^2 + b^2 - r^2 - h^2)}$$

$$E_H = -\frac{2 E_0 h r}{\left(\dfrac{2}{ac^2} + \dfrac{1}{c^3} \ln \dfrac{a-c}{a+c}\right) \sqrt{\xi + a^2}\, (\xi + b^2)\, (2\xi + a^2 + b^2 - r^2 - h^2)}$$

These equations were programmed and a variety of conditions were computed and plotted.

3.2 Theoretical Results

Figure 9 shows two cases of equipotential lines around 30 m high towers of different diameter. Fair weather field conditions of 200 V/m are assumed, however, the equipotential line distribution gives the general picture for any value of the ambient field, requiring only a change in scale. The left plot is of a pointed tower having a 3.3 cm radius of curvature and shows the equipotential lines just around the tower are greatly modified from the parallel field situation. It is striking how closely the lines follow the tower along the vertical structure and how they are concentrated just around the top. But just a short distance away from the tower the parallel field situation is regained. Around the blunt structure with 3.3 m radius of curvature, the picture looks quite different. The equipotential lines are not as closely gathered around the blunt structure as they are around the pointed one, but the field is effected more at greater distances as is apparent by the line concentration. This implies that under appropriate high fields corona ionization occurs only in the immediate vicinity of the sharp point, but over a larger volume around the blunt point.

The field lines run perpendicular to the equipotential lines as represented in Figure 10. The collection area is marked off, for

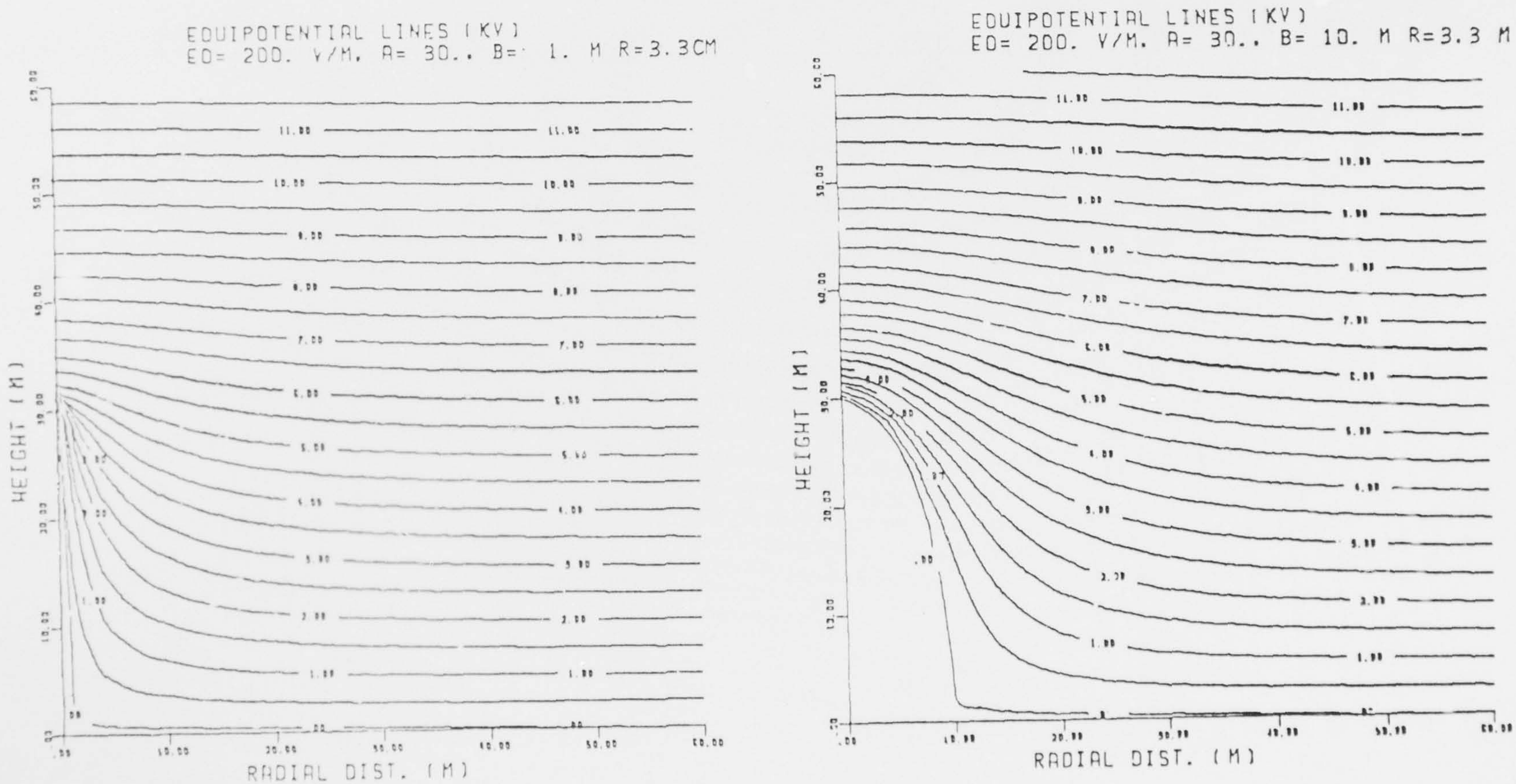
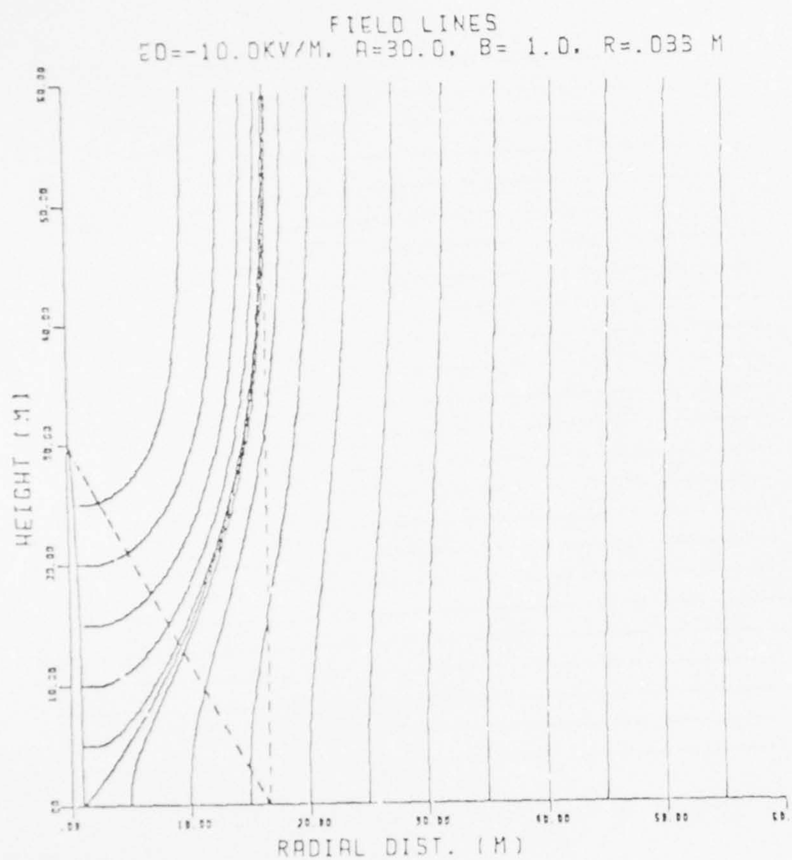


Figure 9. Equipotential lines around pointed and blunt towers.



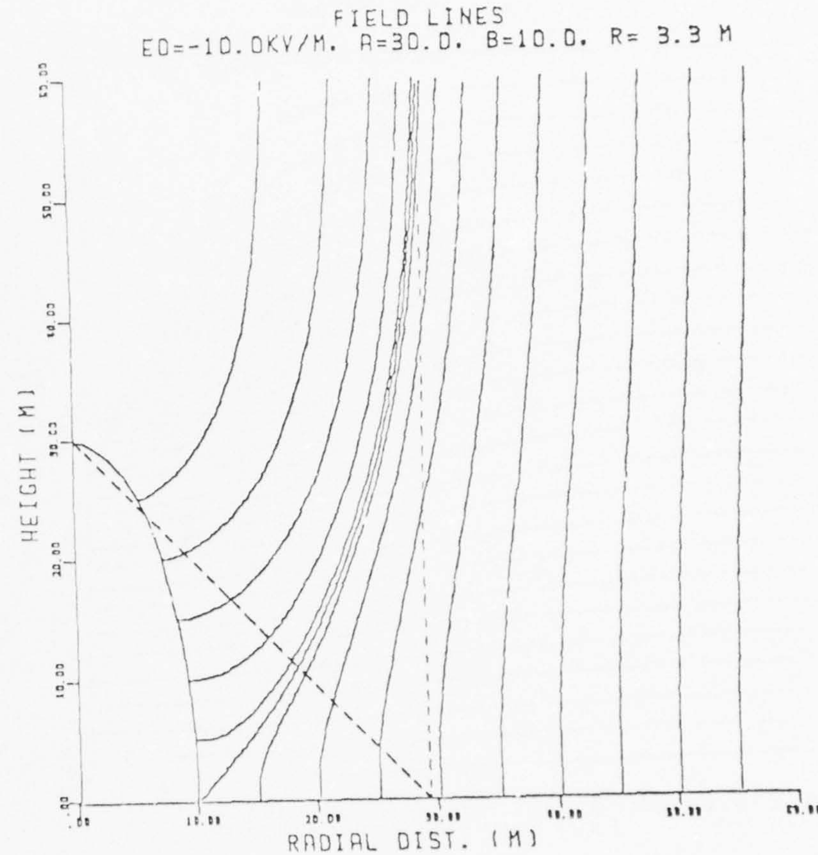


Figure 10. Electric field lines and collection area.

which the field lines terminate on the tower. If a lightning leader was coming down, and the phenomena was assumed very weak, then theoretically it would follow one of the field lines. But of course the high charge carried in a downcoming leader modifies the entire field line pattern.

The exposure factors help determine how soon and out to what distance a tower will go into corona. Figure 11 shows two 30 m high towers with radius of curvature of $\frac{1}{10}$ mm and 10 cm. Lines of equal value were drawn for the exposure factors in an area around the top of the towers, using double logarithmic scales to show detail near and far. Starting from the tower top upward, conditions were examined $\frac{1}{10}$ mm, 1mm, 1cm, 10cm, 1m above the tower; the same was done going down from the top and going outward from the center. The discontinuity in the center of the graph, where the data sets are merged, is insignificant. The enhancement at the tip is of the order of 10,000 for the sharp point, but only 100 for the blunt point. This means that only fields of the order of 100 V/m are required for the sharp point to be in corona, which is in agreement with experimental results from a sharp point giving up to $\frac{1}{4}$ μ amp current in fair weather fields. For the blunt point however, conditions of 10,000 V/m are required before corona is given off. It should be noted that the enhancement for the sharp point drops off rapidly with distance, it is down to a factor of 10 only 30 cm above the tip. The enhancement of the blunt point is larger at these distances and drops down to 10 only at twice this distance, or 60 cm above the top.

The sharp point goes into corona in low fields and just immediately around the tip, the blunt point goes into corona only in high fields but out to greater distances from the tower.

In Figure 12 the exposure factors are plotted versus height for two values of radius of curvature, 1mm and 3.3 cm. This data can be useful in correlating measurements from different heights, or for determining

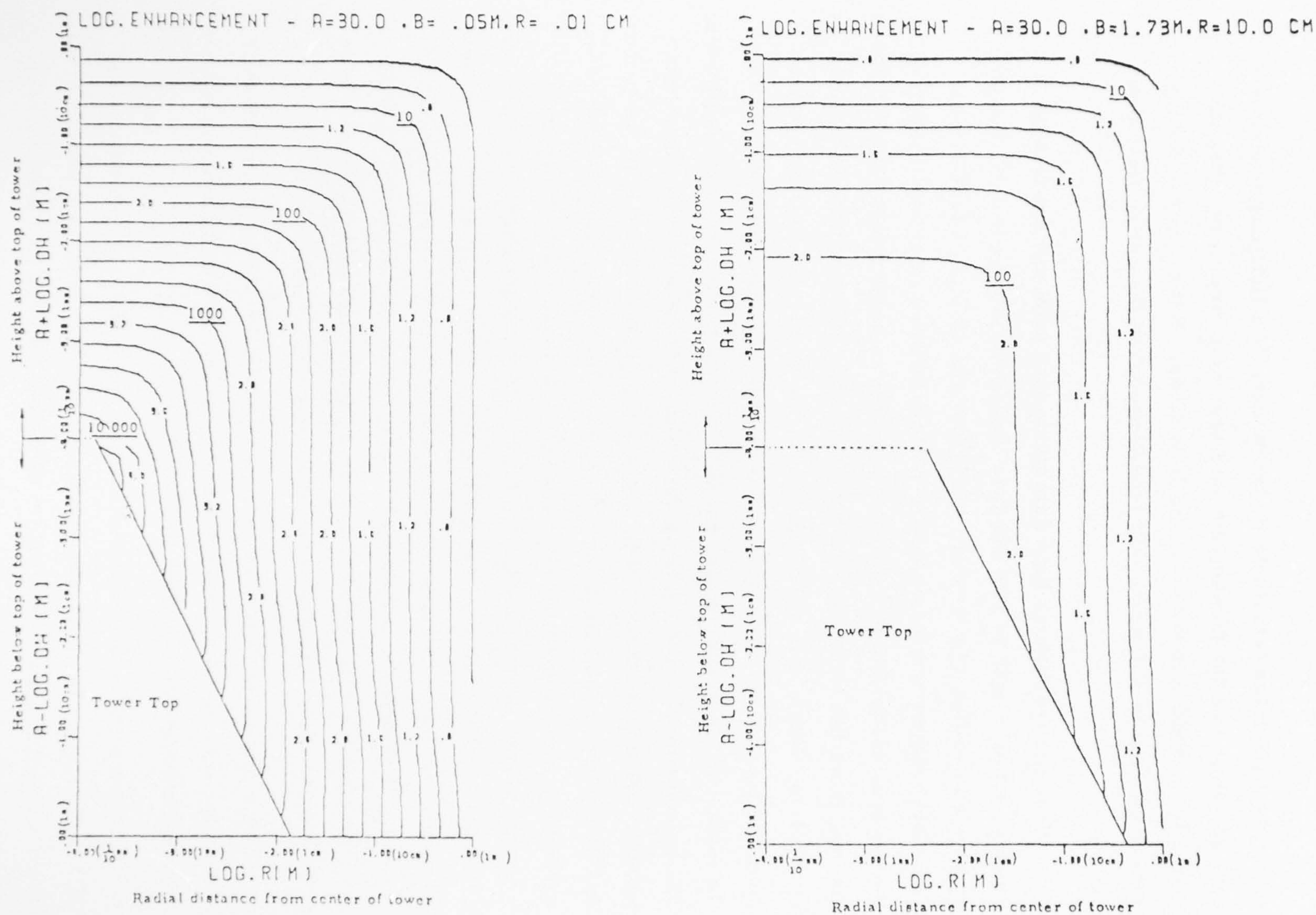
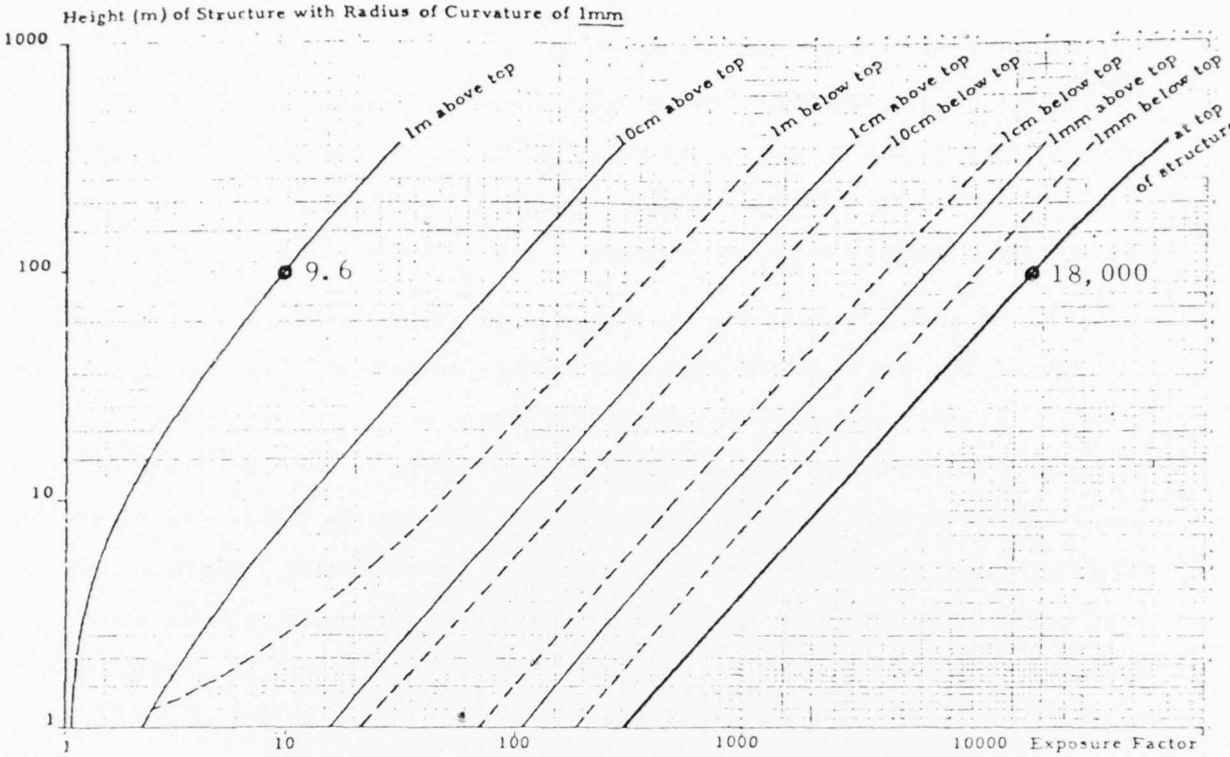


Figure 11. Lines of equal value for exposure factors around sharp and blunt structures.



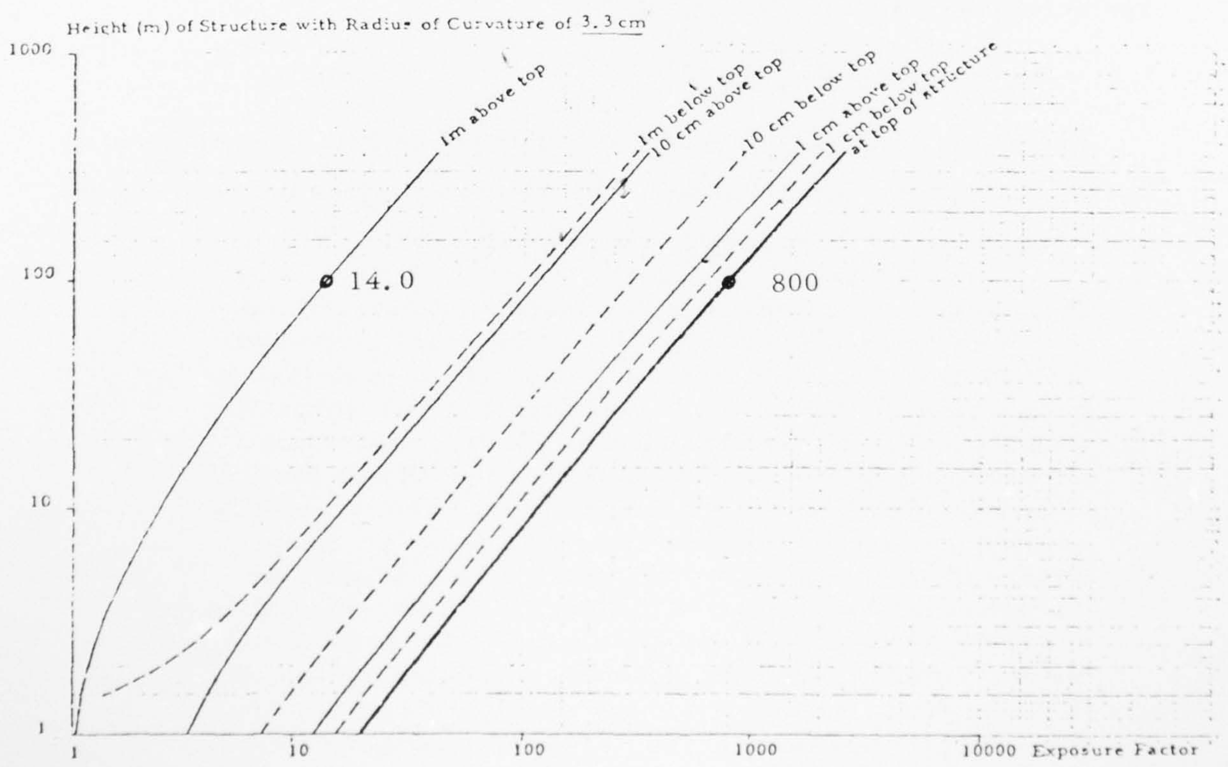


Figure 12. Exposure factors at top of structures, vertically above, and below at side of structures.

the minimum height of a structure for corona breakdown to occur, given the values for the ambient field and the sharpness of the structure. The thick line gives the enhancement relationship at the top of the structure, the solid lines are valid at distances vertically above the structure, and the dashed lines are valid at the edge of the structure below the top.

The exposure factors for the sharp point are very large immediately around the tip, but they are exceeded by the exposure factors for the blunt points at greater distances out from the structures, say 1m above. This indicates that when the blunt point goes into corona it will do so over a much larger volume, but this will only happen when the fields are exceptionally high as is the case in close proximity to an advancing lightning leader. It is highly likely therefore, that a lightning rod with a blunt point will attract lightning to it much easier than a sharp point would do at the same location. Results such as these were the reason why a ball was placed on top of the lightning rod standing on the Saturn launch hardware during the Apollo launches from Cape Kennedy.

3.3 Experimental Results

Experimental results on sharp and blunt points have been obtained by Dr. C. B. Moore of New Mexico Tech, who summarizes the behavior of the lightning rod in the following paragraphs:[6]

> "Benjamin Franklin invented the lightning rod around the year 1749 when he discovered that a sharpened metal rod brought near a charged isolated ball could cause electricity to flow through the air and to discharge the ball without a visible spark. This observation led him to suggest that elevated, sharpened rods might possibly discharge thunderclouds and thus prevent the occurrence of lightning. When he tried out his idea, he found instead that his elevated, metal rod often became a preferential path to ground for the lightning which occurred despite his efforts: his lightning rod had a different mode of operation than the one that prompted his experiment. Franklin thereafter promoted the use of lightning rods, but adhered to the view that they should be sharpened in the hope that the first process might also occur and thereby be beneficial.

Two schools of thought subsequently developed: one favored Franklin's sharpened rod for lightning protection and the other, the English school led by Benjamin Wilson and George III, urged the use of blunt lightning rods on the basis that sharpened rods might promote the striking of lightning when otherwise a discharge would not have occurred. Contemporary American practice is to use sharpened lightning rods, but appreciable evidence exists that objects within the nominal "cone of protection" of a sharpend rod can be struck by lightning and no explanation for this behavior has been suggested.

We have modelled lightning rods both numerically and experimentally to determine their response to an approaching lightning streamer. Our results indicate that lightning can be induced to 'strike' any surface, but that a sharpened rod is much less likely to be 'struck' than a blunt one. Sharpened rods seem to protect themselves appreciably by the copious emission of point discharge ions so that they are poorer candidates to launch an upward-going return streamer when lightning approaches than is a blunt rod which is passive until the field becomes very strong. When the electric field becomes sufficiently strong over a blunt rod, dielectric breakdown of the air occurs at the blunt tip and a streamer propagates upward and often participates in a major discharge. For these reasons it appears that a blunt rod may be a better protector of a structure than is a sharpened one which may protect itself but leave other objects in its vicinity vulnerable.

Perhaps more attention should have been given to the opinions of George III!"

An example of experimental results by Standler[7] is given in Figure 13, where the current and charge release of a blunt and sharp rod are presented that were obtained in response to two close lightning strokes monitored by the electric field. The blunt rod emitted $+11\mu$ coulomb in less than 10 msec from the first field pulse received from the lightning flash, while the sharp rod released only $+2.2\mu$ coulomb. During the first 460 msec of this flash the charge transfer for blunt and sharp rods are +25 and $-8.3\ \mu$ coulomb respectively. The corona current graphs also illustrate that under the extremely high fields of close lightning much more current is given off by the blunt rod than by the sharp one.

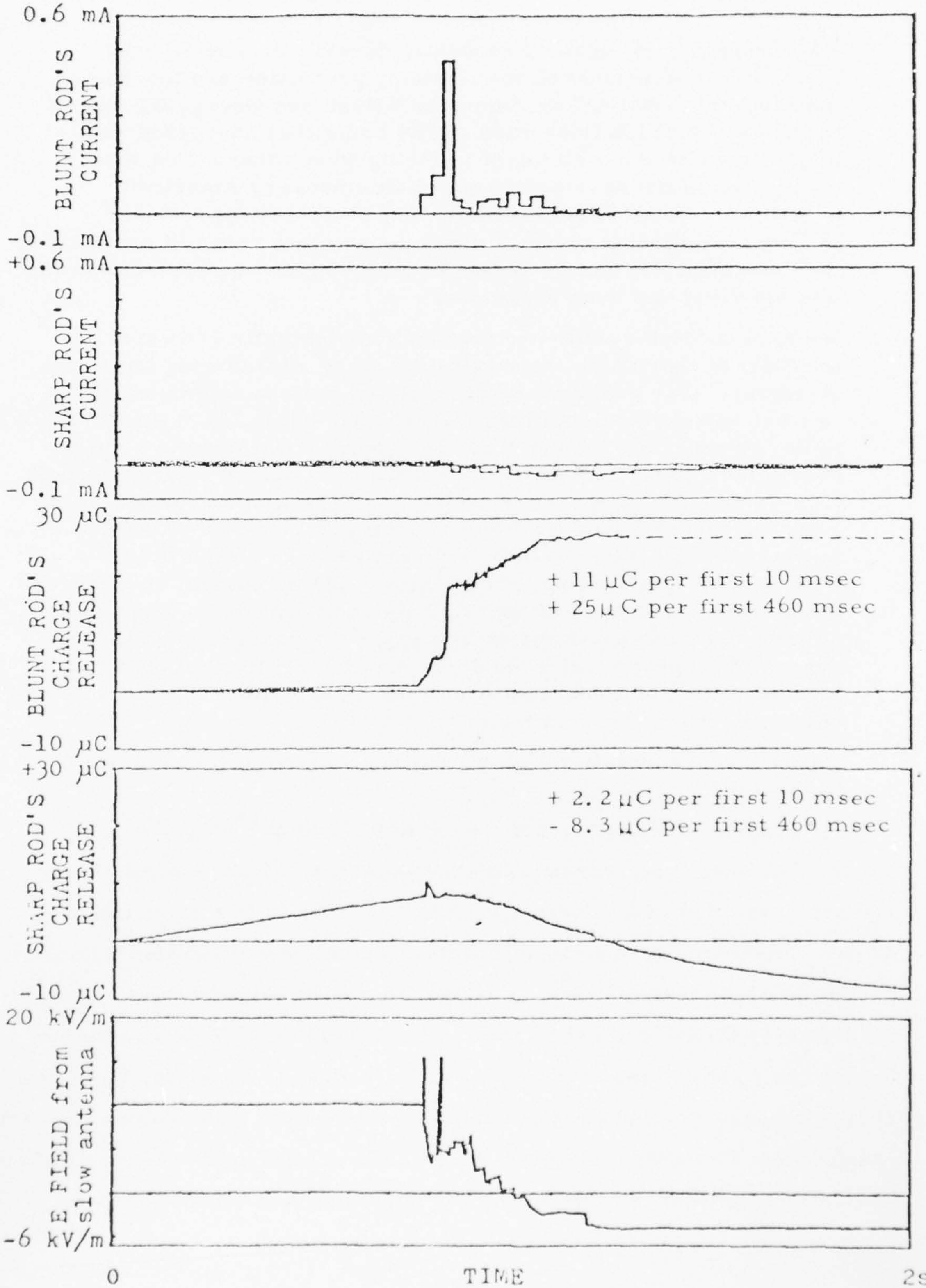


Figure 13. Lightning (0.4 km distant) at 1142:12.00, 18 Aug 1974.

4.0 ANALYSIS OF THE LOGAN AIRPORT NOISE PROBLEM

The radio noise that occurs under high field conditions at VHF frequencies and occasionally on UHF receivers can be generated from one of several sources:

1) Corona discharge under high ambient field conditions from,

   a) the lightning rod on top of the radome.
   b) the lightning rods around the parapet.
   c) the antennas around the parapet.

2) Corona discharge in high fields due to the radome charge.

3) Streamer noise from the radome surface.

4) Charge transfer to the antenna rods from rain.

In order to attempt to determine the specific source of noise and to deduce the onset conditions, measurements of electric field and corona current were taken at Logan Airport, theoretical calculations were performed, and the results of both were correlated. The contract which led to this report was for only a few days analysis; detailed investigations were not possible and the conclusions presented should be treated as a starting point for a thorough analysis which must be performed if the problem at many ATCT locations is to be overcome.

4.1 Effect of the Static Dischargers

It is necessary first to analyze the corrective procedures which have been carried out at several ATCT locations with a certain amount of success, namely the use of the P-static dischargers. The devices are designed to bring the potential of the structure on which they are fastened to the potential of their surroundings. In this case, the lightning rod is at the potential of the control tower and ground, and there is absolutely no way that one can dissipate the charge on the grounded elevated structure to bring it to the potential of its surroundings. Apart from this, it is unlikely that corona will occur at the P-static dischargers which are installed in an area of reduced field underneath the grounded cross-member. Corona discharge

only occurs in high field areas. No matter how many P-static dischargers were connected to the tower, the lightning rods would still remain at ground potential, the field above would be unchanged and corona would still form there.

The question remains, therefore, as to what caused the improvement when the devices were attached to the lightning rods? The answer is quite simple and can be explained again by looking at Figure 9. Around the sharp point the equipotential lines hug the structure. If we now introduce a grounded horizontal cross-member, which subtends an angle of almost 90° at the top of the lightning rod, then the equipotential lines must pass around it in a way similar to that shown in Figure 14.

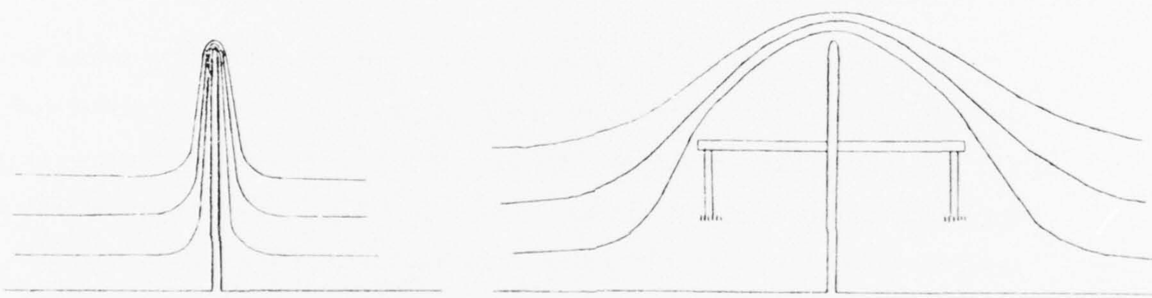


Figure 14. Equipotential Lines around Lightning Rod before and after Installation of Static Dischargers

The effect is to lower the potential gradient at the tip by making the structure look electrically more like a rounded object. This reduced potential gradient makes it necessary for a much larger electric field to be present before corona breakdown is initiated.

Placing the cross-member lower would mean that corona would occur earlier as the field at the tip would increase; placing it higher delays the onset of corona until the electric field is exceptionally high. Care must be taken, however, not to lift the horizontal member too high to avoid corona being formed on its extremities. The above figure shows that no corona will be forthcoming from the P-static dischargers, owing to its environment being a low field condition.

4.2 Determinations of Electric Field and Corona

4.2.1 Lightning Rod on Top of Radome

Theoretical estimates can be made of the fields under which the highest lightning rod on top of the radome will go into corona. Verifications with measurements could unfortunately not be obtained because the top was inaccessible due to high winds during the brief test period. For an air terminal with a radius of curvature of 1mm, which is not particularly sharp, placed on top of a very narrow grounded structure of the height of the control tower of about 300 ft, an enhancement of about 18,000 above the ambient electric field can be determined at the tip of the rod from Figure 12. As a result of the radome and the wide grounded structure below it, however, the exposure factor at the tip of the air terminal on top of the radome is much lower.

Calculations were performed to approximate the Logan tower situation. A 4 ft rod with 1/2 mm radius of curvature was considered, placed on top of a rounded structure with a 19 ft diameter at the top and 112 ft at the bottom. The exposure factor at the tip of the rod was determined as 1,700. For Logan Airport this figure is representative for the field enhancement at the top, but for other similar control towers without a radome and with an effectively higher lightning rod, the field enhancement could be very much higher.

Under fair weather fields of say 200 V/m, the field at the tip of the highest Logan Airport lightning rod will be over 1,700 x 200 V/m, or above 340,000 V/m which is not enough for corona breakdown. Assuming a starting potential of 10^6 V/m for corona, we need a field of 600 V/m at ground level to cause breakdown at the point. Such a value will occur prior to thunderstorm onset, and later in the storm the fields may reach values in excess of 10,000 V/m. With these fields more current will flow and the radio noise will reach a level above the receiver noise level.

The onset of corona can be delayed by modifying the radius of curvature of the rod. By placing a 10 cm diameter corona ball over the

tip of the air terminal, the exposure factor on top would be reduced by a factor of about 8 to around 210, and ambient fields of at least 4,800 V/m are then required instead of the low 600 V/m fields to cause corona breakdown. This modification, however, will not eliminate corona. Removing the rod altogether will result in an enhancement of 23 over the ambient field right on top of the radome, a figure low enough to suppress corona breakdown even under storm conditions. Only the fields of an approaching lightning leader would then be large enough to cause corona, however, the tower would be without lightning protection.

4.2.2 Lightning Rods and Antennas around Parapet

It is difficult to theoretically come up with reasonable enhancement figures for the complex layout of lightning rods and antennas around the parapet, hence it was necessary to take measurements to determine these values. Two field mills were run simultaneously, one at ground level and one on the parapet around the radome. This gave a calibration for the enhancement over the ambient field at the second field mill location. Then two field mills were run simultaneous, one at the calibrated reference location on the parapet, and with the other one measurements were taken at the locations and heights of the lightning rods and antennas around the radome. From these data the enhancements over the ambient field were computed at the rod locations in the presence of the field mill which resembles a blunted object. With the aid of theoretical calculations, correction factors were applied to these numbers to determine the exposure factors at the tips of the air terminals and antennas unmodified by the presence of the field mill.

These results are shown in Figure 15. The exposure factors are largest for high rods with small radius of curvature well separated from other rods and field reducing structural features. The highest electric fields are above the sharp points of the 6 ft air terminals. The fields are significantly lower above the blunt, 1" diameter VHF antennas which are

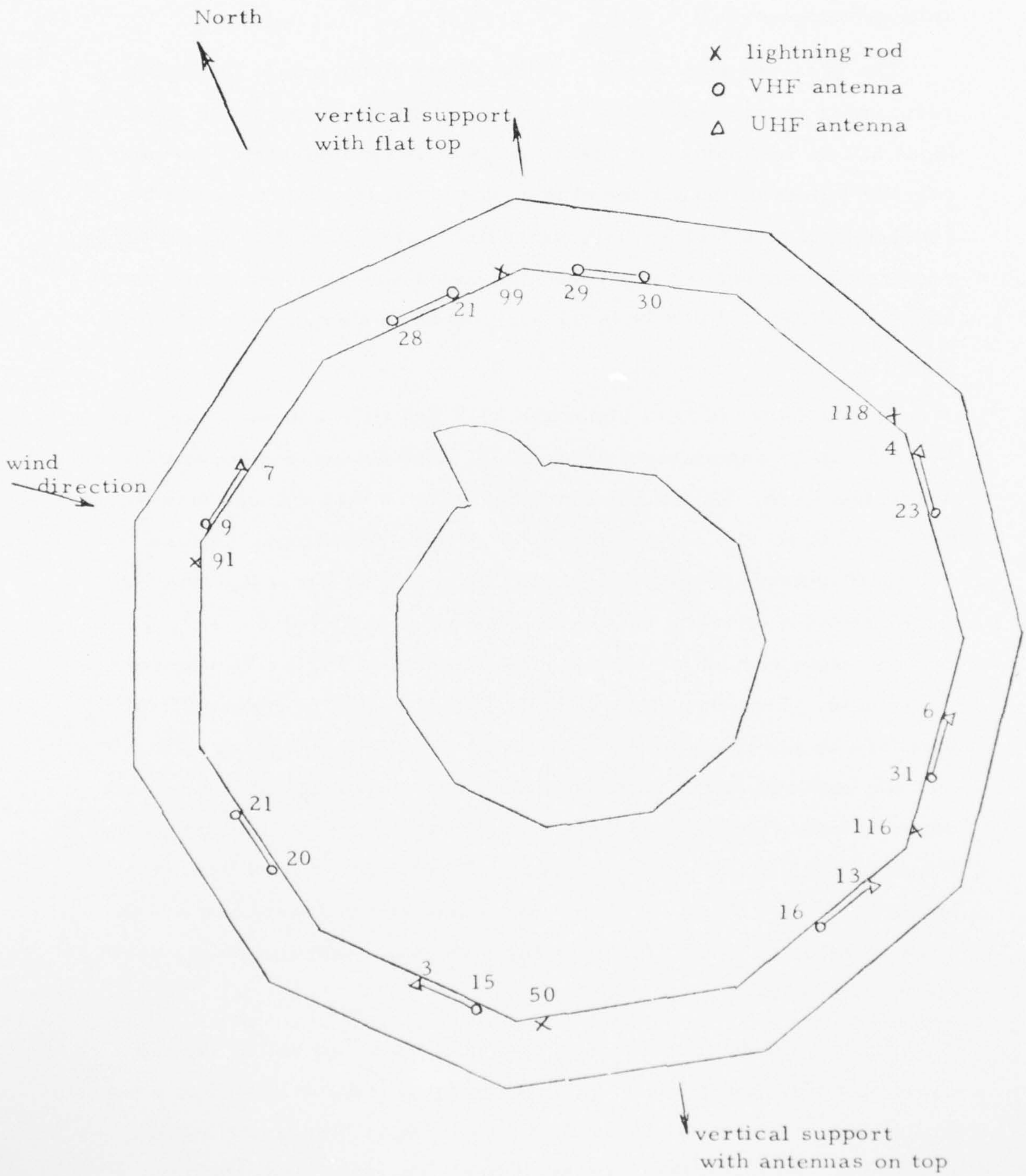


Figure 15. Exposure factors versus ground on top of the lightning rods and VHF antennas on the Logan International Airport air traffic control tower.

nearly 5 ft high, and even much lower above the wide 3 ft high UHF antenna structures.

The greatest enhancement of 118 exists above one of the lightning rods; under storm conditions with ambient fields above 8,500 V/m the point will be in corona. If corona balls of 10 cm diameter were placed over the points of the air terminals, the exposure factors would be reduced by a factor of 8 and ambient fields of 68,000 V/m would be required for corona onset. Such high fields are not found under usual storm conditions, but only in the vicinity of an approaching lightning leader.

The exposure factors above the VHF and UHF antennas vary between 3 and 31 and ambient fields of 32,000 V/m and higher are required for corona onset. It can therefore be assumed that the antennas will probably not go into corona even under storm conditions. Corona measurements were taken at several locations on top of the tower and were related to electric field data in order to understand the field line concentration around the tower. The diagram in Figure 16 illustrates the results. The edge of the parapet is in a region of reduced field produced by the shape of the structure. The field increases in a radially outward direction and reaches a maximum at about 4.5 ft out beyond which it decreases again. The largest corona currents were measured as 2.3 μA and associated with fields of 100,000 V/m in the dense field line region. The corresponding ambient field had a high positive value of 1,200 V/m probably caused by snow conditions north of the Boston region.

Similar corona measurements were taken below and above the lightning rods, and it was found that the tip of the rod is still in a reduced field. Three feet above its tip the field is four times as large as 1 ft above. To fulfill the purpose of lightning protection, the air terminals must have a minimum height of 6 ft, which is just 1 ft above

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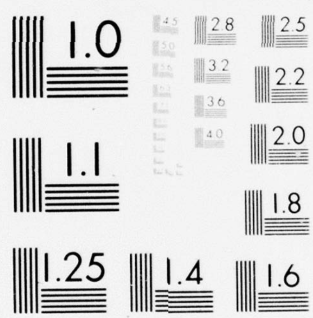
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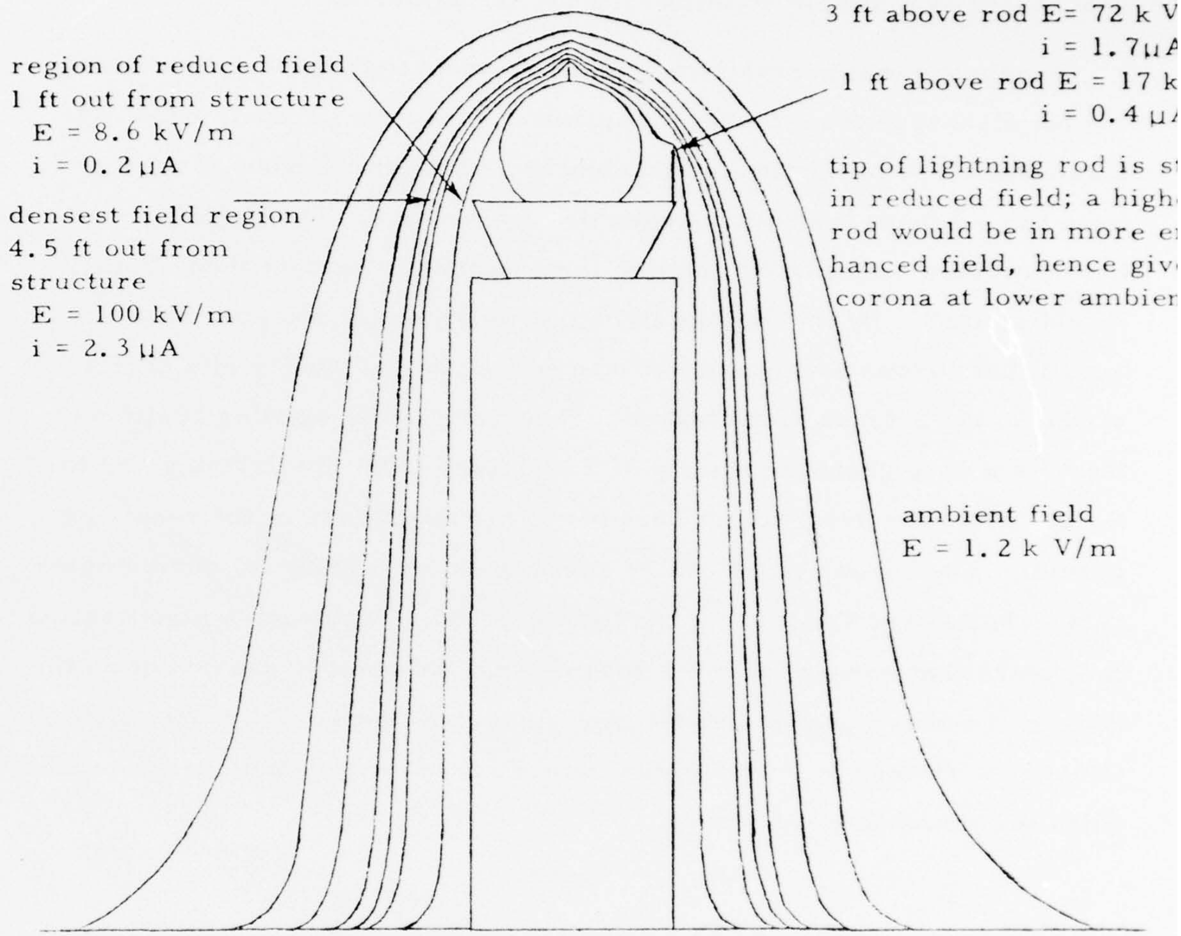

Figure 16. Equipotential lines around structure go through enhanced density 4.5 ft out from structure as determined from corona current (i) measurements.

the height of the VHF antennas. If the lightning rods, however, were much higher, then their points would be in a more concentrated field line region, and corona onset and associated noise problems could be much more frequent and persistent. Raising the lightning rods to move the corona source further away from the antenna, can therefore not be considered as a simple solution to the noise problem.

It appears that currently the noise problem may be associated with corona discharge from the lightning rods around the parapet, which are located in close proximity to the receiver antennas. Corona discharge from the antennas themselves does not seem likely. The lightning rods have probably been placed close to the antennas to protect them from direct strikes. By moving the lightning rods further away we have the result that corona noise may be reduced but the possibility of a direct strike to the antenna is increased. However, in the existing positions there is a very great possibility of a sideflash from the lightning rod to the antenna over several feet because of the inductance of the receiving system. The corona onset can be suppressed by placing 10 cm diameter corona balls over the point of the lightning rod. With such a modification it appears that corona from the rods around the parapet should not be the source of a noise problem under high field conditions. Only when lightning is about to strike the tower or the immediate vicinity could corona caused noise problems be experienced.

4.3 Effect of the Radome Charge

Under severe snow and blowing conditions a very large potential difference may occur between the dielectric surface of the radome and the surrounding structures. If this surface has an electric field intensity that is sufficiently high to cause voltage breakdown across the plastic surface, then a streamer discharge may occur which can generate serious radio interference. Near the ocean where high charges exist due to charge separation in breaking waves, such charges may be transported in a high wind and may cause rapid buildup on the radome. Driving snow will also cause a charge buildup. Hence, the possibility that the radome can become sufficiently charged to cause streamer discharges has to be considered.

The charge accumulated on the radome may have a second effect. It may create high enough fields conducive to corona discharge from points in its vicinity such as the lightning rods which are about 4 ft away or the sharp edges of the ladder only 1ft away.

To investigate the magnitude of the charge that may reside on the dielectric surface, electric field measurements were taken a short distance away from some radome panels that were charged by rubbing with a glove. The results are shown in Figure 17. The radome was charged to -29,000 V creating an electric field of -24,000 V/m at a distance of 4 ft at the tips of the lightning rods around the papapet as well as on top of the radome. Since an enhancement of 12 above the ambient field exists 4 ft above the radome in the absence of the air terminal, the charged radome would, at the distance of 4 ft, have an effect equivalent to a change in the ambient field of -2,000 V/m. Whatever the effect is, it would persist for extended periods of time, as it was found that the charge remained on the radome beyond the duration of the experiment and did not drain off.

The field of the charged radome may reinforce or counteract the existing ambient field. It is difficult to estimate the effect on corona formation above the rods, as the equipotential lines there are not normal

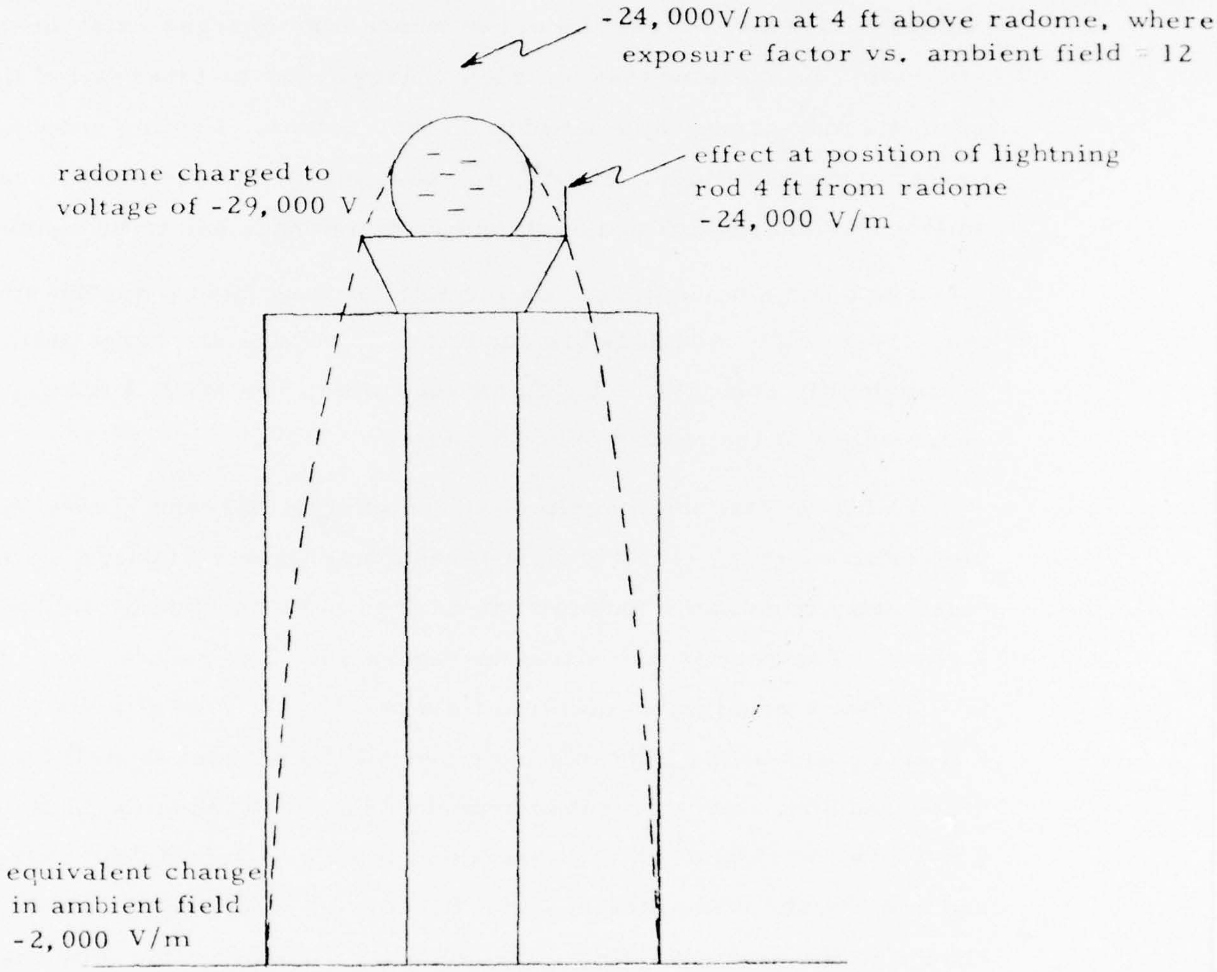

Figure 17 . Effect of radome charge on electric field. (distorted scale).

to the rods, hence their effect is reduced. To understand this problem would require involved computations and additional measurements. At the location of the ladder about 1ft away from the radome the fields, due to the radome charge, are even much higher of the order of -95,000 V/m, and at the ladder support and the bottom of the highest lightning rod the field might be so high that there exists continuous corona discharge. Furthermore, the potential of the radome could reach values much higher than those we caused with a leather glove.

Charge deposited on a dielectric surface such as the radome is bound there because the surface is an insulator. As a results, under precipitation charging conditions, it is possible for a potential difference of tens of kilovolts or more to exist between a dielectric surface and the neighboring structural parts. As charge continues to accumulate on the dielectric, the potential to the structural parts rises until the electric field intensity at the dielectric surface becomes sufficiently high that voltage breakdown or streamer discharge occurs across the plastic surface. A surface streamer involves the rapid transfer of charge over a substantial distance, and also generates serious radio frequency interference.

The degree to which the radio frequency noise generated by corona and streamer discharges couples into electronic systems is determined by the relative locations of the noise source, and the receiving antennas via which the noise is coupled into the affected system. In addition, the coupling depends on frequency and the size of the antennas. This subject is quite complicated and requires further, extensive investigations.

4.4 Charge Transfer from Rain

The charge on rain hitting the receiver antennas will cause a current to flow to ground through the receiving circuit that might be of the same order of magnitude as the normal signals and hence produce noise interference. To investigate this hypothesis, a maximum charge on a single raindrop was assumed as -2.3×10^{-12}C $= -1.4 \times 10^{7}$ electrons from Chalmers.[8] If 100 such raindrops fell on the antenna per second trans-

ferring their charges, a current of 2.3×10^{-4} μA would be flowing. This would result in a voltage of 1.2×10^{-2} μV across the receiver impedance of 50Ω, at a power of 2.6×10^{-18} Watt.

The receivers operate at a signal level of 2.5 to 3 μV with a normal ambient noise level of 1μV, which is about two orders of magnitude greater than the noise attributed to the charge transferred from rain. It is therefore unlikely to be a source of the noise. If, however, the assumed figures of number of drops per second and charge per raindrop do not represent maximum values, then radio interference from charged rain might still be possible. This is more likely to be the case above the Logan tower where the rain may gather an enormous charge due to excessive corona in that environment.

4.5 Summary

Of the suggestions put forward as the sources generating radio noise the possibility of corona discharge appears to be the most likely one. Corona from the antennas seems unlikely, corona from the lightning rod on top of the radome may possibly cause interference, and corona from the air terminals around the parapet seem to be the most likely source because of their proximity to the receiver antennas. A modification was suggested that would eliminate the corona discharge from the lightning rods under usual storm conditions, and it consisted of 10 cm diameter corona balls to be placed over the tip of the lightning rods giving them a blunt appearance. This modification is also thought to enhance the lightning protection capabilities.

The effect of the charge on the radome in the form of streamer discharges or corona from close points was recognized as important, but could not be well defined as to its severity. It was determined however, that once the radome was charged, it would hold its potential for a considerable period of time, resulting in prolonged effects.

The charges on raindrops being transferred to the antennas are not believed to establish a large enough current flow, and hence are not likely to be the source for radio noise, but this assumption is based on rain charge measurements under very different situations.

One must realize that the conclusions presented here should only be treated as a starting point for a thorough analysis. The corrective measures of adding corona balls might eliminate the most significant contribution to the noise problem, but other structures nearby may still cause corona noise. The effects of the charge on the radome and charge transfer from raindrops have also not been well identified, and interference may be recurring. The problem must be understood in detail. It is necessary to know the receiver noise level as a function of distance from the source, source magnitude, frequency and antenna gain. Once such tests have been performed it should be easy to make recommendations for lightning rod radius of curvature and distance from a particular antenna.

5.0 PROPOSAL FOR TESTS LEADING TO GENERAL RECOMMENDATIONS ON ELIMINATING RADIO NOISE

A single coordinated study for a few months on the VHF radio noise problems that are a hazard at many ATCT locations around the country would save considerable time and effort which is at present, being expended by many engineers from Boston to Chicago to Denver and Seattle.

The tests could be performed at any establishment where VHF and UHF receivers could be made available, but there would be many advantages in carrying out the experiments at an ATCT location such as at Logan Airport.

It would be necessary to have receivers and antennas similar to the ones used at ATCT locations. A lightning rod would be modified to allow corona current measurements to be made at its base using a 10 ohm series resistor and pre-amplifier capable of allowing recording of currents to better than $0.25\mu A$. The receiver noise level would be monitored as a function of corona current and distance of the antenna from the corona source.

The experiments would be repeated for different radii of curvature of the rod, as more active corona around a sharp point possibly emits more radio noise than a similar corona current from a blunter rod under higher field conditions. At this time a relationship would be established relating corona current to radio noise as a function of distance and point sharpness.

It would then be necessary to relate lightning rod corona current to the unperturbed electric field as a function of control tower height and geometry. This could be achieved by both experimental and theoretical experiments computing enhancement factors. A field mill would be located at ground level on flat terrain away from any large obstructions, such as in the center of an airfield. The electric field values at that point would be correlated with those on top of the control tower and at various points around

the region of the VHF/UHF receiving antennas. This data, along with theoretical data similar to that shown in Section 3, would lead to a relationship between corona current and unperturbed electric field as a function of lightning rod position, height and sharpness.

Recommendations would then be made relating the worst expected electric field data to the likelihood of radio noise for different antenna locations. This information should allow the selection of suitable sites for the receiving antennas, or corrective measures to the lightning rod position and sharpness in order that radio noise be eliminated.

It is worth noting that it is possible to install a simple field monitoring device that would warn an observer of high electric fields in his environment and hence, the possibility of radio interference. Such a device may be useful if the geometry and height of a receiving site is such that some local corona sources could not always be suppressed.

6.0 REFERENCES

1. Trichel, G. W., The mechanism of the negative point to plane corona near onset, Phys. Rev. 54, 1078-84, 1938

2. Chapman, S., Corona point current in wind, JGR, 75, 2165-69, 1970.

3. Nanevicz, J. E., D. G. Douglas, Static-electricity analysis program, SAMSO TR 75-44, 1974.

4. Stratton, J. A., Electromagnetic theory, McGraw Hill, N.Y., 1941.

5. Morse, P. M., H. Feshbach, Methods of theoretical physics, McGraw Hill, N. Y., 1953.

6. Moore, C.B., Research into cloud electrification and its modification, Response to RANN Questionaire, 1977.

7. Standler, R. B., The response of elevated conductors to lightning, MS thesis, New Mexico Tech, 1975.

8. Chalmers, J. A., Atmospheric electricity, Pergamon Press, New York, 1967

FEDERAL AVIATION ADMINISTRATION EARTH RESISTANCE

FIELD TESTING METHODOLOGY

(FAA FIELD TESTING METHODOLOGY)

by

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Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

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ABSTRACT

Significant parameters which contribute to resistivity magnitudes are discussed. Resistivity values from referenced sources as well as those measured by NAFEC personnel are presented.

The design of an XIT ground rod testing program is outlined. XIT ground rod resistance performance is compared with copper clad steel rods and these steel rods enhanced with salt rings. XIT rods are described; resistance measurement data is presented and discussed.

Resistivity measurements at several Federal Aviation Administration facilities are discussed. These measurements employed the four probe measurement technique. Utilizing these resistivity values, resistance computations are presented for a grounding configuration consisting of ground rods interconnected with buried bare wire. Formulas used to obtain calculated resistances are presented and limitations on their accuracy are addressed. Calculated versus measured resistance values are shown. The importance of a survey to obtain pertinent data on which to base a design of a grounding configuration is discussed. Alternative ground counterpoise designs are suggested.

It is concluded that: (1) XIT ground rods provide lower resistance than standard copper clad steel rods and the variability of this resistance versus time is significantly less. (2) Where high earth resistivity magnitudes are encountered, it may be economically infeasible to obtain a desired resistance.

INTRODUCTION

The Federal Aviation Administration (FAA) has been recently involved in XIT rod resistance and earth resistivity measurements. The XIT rod is a chemically filled pipe serving as a ground rod. The XIT rod task involved the development of test criteria, the selection of test beds, the installation of test samples, and the collection and analysis of data.

The earth resistivity measurements were taken at planned field sites for Air Route Surveillance Radars (ARSR) and at XIT rod test bed locations. Measurement results are presented and approximations of ground configuration resistances are calculated for ARSR sites.

RESISTIVITY

Resistivity is the resistance times the cross section area divided by the length:

$$\rho = \frac{RA}{L}$$

where ρ is in ohm-meters
R is in ohms
A is cross sectional area with dimensions in meters

Resistivity of copper at room temperature is 1.7×10^{-8} meter-ohms. Tungsten is 2.5, zinc 3.3, iron 6, lead 12 and brass four times the resistivity of copper.

The resistivity of the earth covers a wide range. Figure 1 shows estimated average resistivity values in the United States. Area values are 33, 67, 125, 250, 500, 1000, and 2000 meter-ohms. As far as earth ground configuration installations are concerned, the lower the number the better. Table 1, Geological Period and Formation, lists earth resistivity values by geological periods and formation. Values range from 1 to 10,000 meter-ohms. Table 2 lists soil resistivity values measured at various FAA locations. Table 2 values were obtained by using the four probe method with a Biddle meter. Values range from 10 to 29,000 meter-ohms.

Resistivity is dependent upon type of soil, moisture content of soil, temperature of the soil, porosity of the soil, and chemical content of the soil. Since these parameters may differ with the depth of layers or combinations of layers in the earth resistivity may vary with depth. A general note regarding concrete below ground level is that it is a semi-conducting material with a resistivity of about 30 meter-ohms at 20°C.

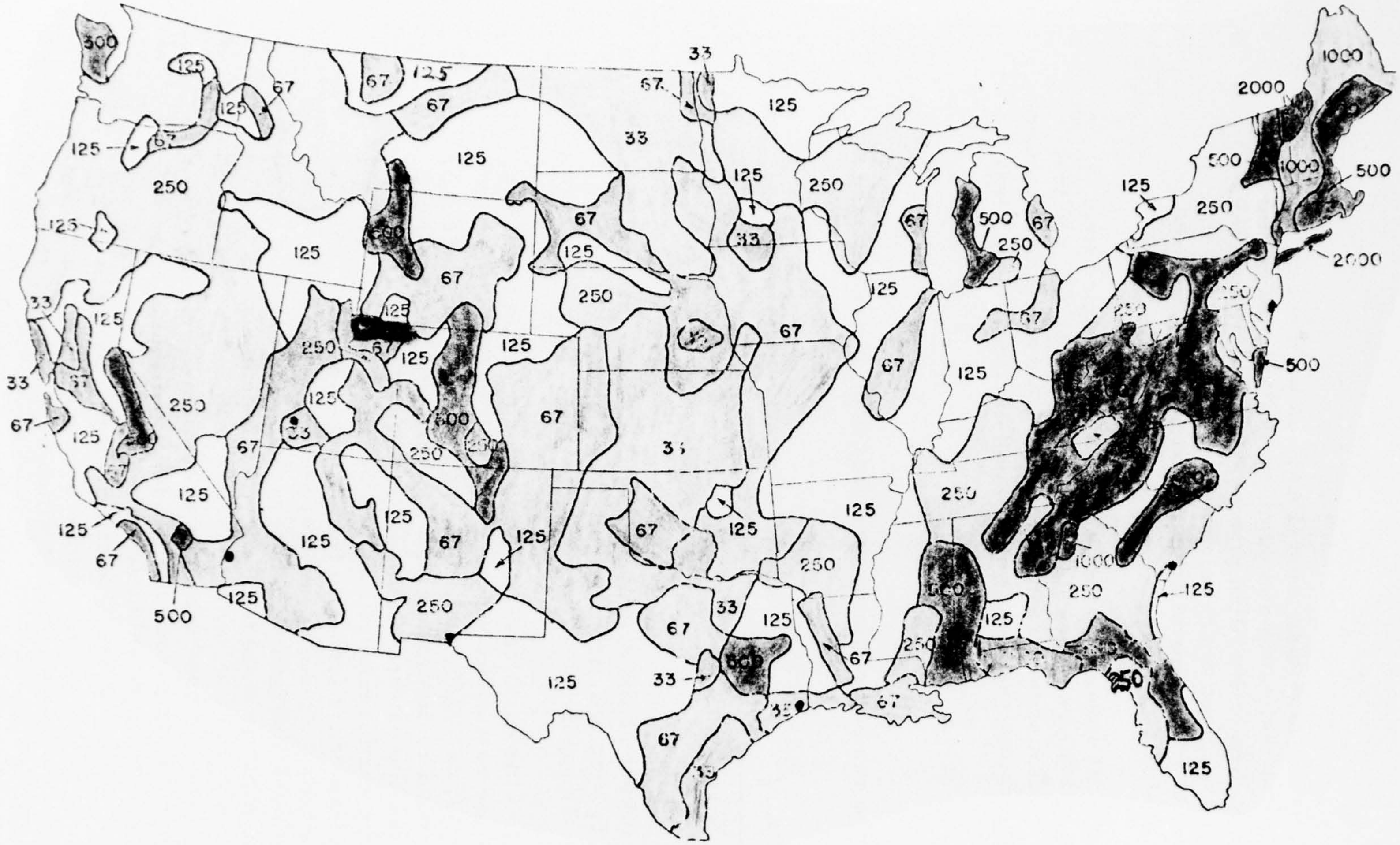


FIGURE I. ESTIMATED AVERAGE EARTH RESISTIVITY IN U.S. (METER-OHMS)

TABLE 1 - GEOLOGICAL PERIOD, FORMATION AND RESISTIVITY

Earth Resistivity Meter-Ohms	Quarternary	Cretaceous Tertiary Quarternary	Carboni-ferous Triassic	Cambrian Ordovician Devoman	Pre-Cambrian & Combinat with Cambrian
1 Sea Water					
10 Unusually Low		Loam Clay Chalk			
30 Very low			Chalk Trap Diabase		
100 Low					
300 Median			Shale Limestone Sandstone	Shale **Limestone** Sandstone Dolomite	
1000 High					Sandstone
3000 Very High	Course Sand				Quartyite
10,000 Unusually High	and Gravel in Surface Layers				Slate Granite Gneisses

NOTES

Quarternary - Recent Period - in last 2 million years
Tertiary - 10-70 million years ago
Cretaceous - 130 million years ago
Carboniferous - 340 million years ago
Cambrian - More than 340 million years ago

TABLE 2 - RESISTIVITIES AT VARIOUS FAA LOCATIONS

LOCATION	RESISTIVITY METER-OHMS	TYPE SOIL	SURFACE TEMPERATURE (F)	MOISTURE CONDITIONS	SURVEY DATE
Beaumont, Texas	9.28	Gumbo	75°	Moist	4/13/76
El Paso, Texas	61.82	Dusty	76°	Dry	4/14/76
Tobe, Colorado	154.85	---	88°	Dry	5/11/76
Thatcher, Colorado	260.	Loam Limestone Rock	88°	Dry	5/11/76
Phoenix, Arizona	267.98	Sand with pebbles mixed	100°	Dry	5/13/76
Wildwood, N.J.	327.86	-----	92°	Dry, Water Table 6 foot	6/11/76
McDill AFB Florida	691.36	Loam	44°	Moist, Water Table 6 foot	2/8/77
Duette, Florida	1466.02	Sand	44°	Dry	2/9/77
NAFEC	3688.	Road Gravel	72°	Dry	4/22/76
Tampa, Florida	6070.92	White Sand	----	----	2/9/77
Fletcher, Florida	16326.	Sand	50°	Dry	2/9/77
Bell, Florida	25892.35	Sand	44°	Dry	2/8/77
Chesterfield, S.C.	29956.	Sand Porous	61°	Dry	2/10/76

XIT RODS

These rods are chemically filled copper ground electrodes. They are patented by XIT Rod Company, Covina, California. The diameter of the rod is 2 1/8" O.D., the wall thickness .083". The material is copper. These rods can be ordered in eight feet, ten feet, and twenty feet lengths. Where bedrock is encountered L shape rods can be provided. Atmosphere moisture is absorbed by the salt contents and the resulting chemical solution seeps into the soil lowering the resistivity of the soil.

XIT ROD TEST DESIGN AND INSTALLATION

Two ten foot 5/8" copper clad steel (CCS) ground rods were driven into the soil at the same time as the XIT rod was installed. One of these CCS rods had a salt ring two feet inner diameter and four feet outer diameter and dug to a foot depth. A ten foot hole was augered; five pounds of table salt and four gallons of water were placed at the bottom of the hole and the XIT rod placed therein. The hole was then backfilled and tamped. The three ground rods were placed 30 feet apart. Test bed selection criteria were: (1) low earth resistivity area of zero to 300 ohms per meter in both moist and dry regions (2) medium earth resistivity area of 301-600 ohms per meter in both moist and dry regions and (3) high earth resistivity area of 601 ohms per meter and above in moist and dry regions.

Using the Biddle earth tester as the measurement device and the four probe measurement method test sites were selected. The sites, resistivity range, and moist or dry classification are shown in Table 3. Calculated resistance versus measured resistance of the sites is also shown in Table 3.

XIT ROD TESTING RESULTS

Figures 2-8 are plots of resistance versus time for the three type rod configurations at several locations. The XIT rods provide lower resistance grounds than copper clad steel rods with or without a salt ring and the resistance variability versus time is less. The copper clad steel salt added rod provides lower resistance and the resistance variability versus time is less than the copper clad steel rod.

TABLE 3 - GROUNDING ROD TEST SITES/RESISTIVITY AND RESITANCE VALUES FOR COPPER CLAD STEEL ROD

LOCATION	BIDDLE METER READING	RESISTIVITY METER-OHMS	CALCULATED RESISTANCE OHMS	MEASURED RESISTANCE OHMS	INSTALLATION DATES
Beaumont, Texas	.48	9.28	(4/13/76) 2.98	(8/16/76) 3.08	8/76
El Paso, Texas	3.23	61.82	19.41	19.1	4/76
Phoenix, Arizona	14	267.98	85.74	69	8/76
Wildwood, New Jersey	17.43	327.86	(6/11/76 205.37	(8/9/76) 150	6/76
Phoenix, Arizona (Site2)	62.5	1196.34	384.5	To be measured	To be installed
NAFEC	187.5	36.88	1180	495	10/75
Chesterfield, S. C.	1565	29956	9586	>10,000	2/76

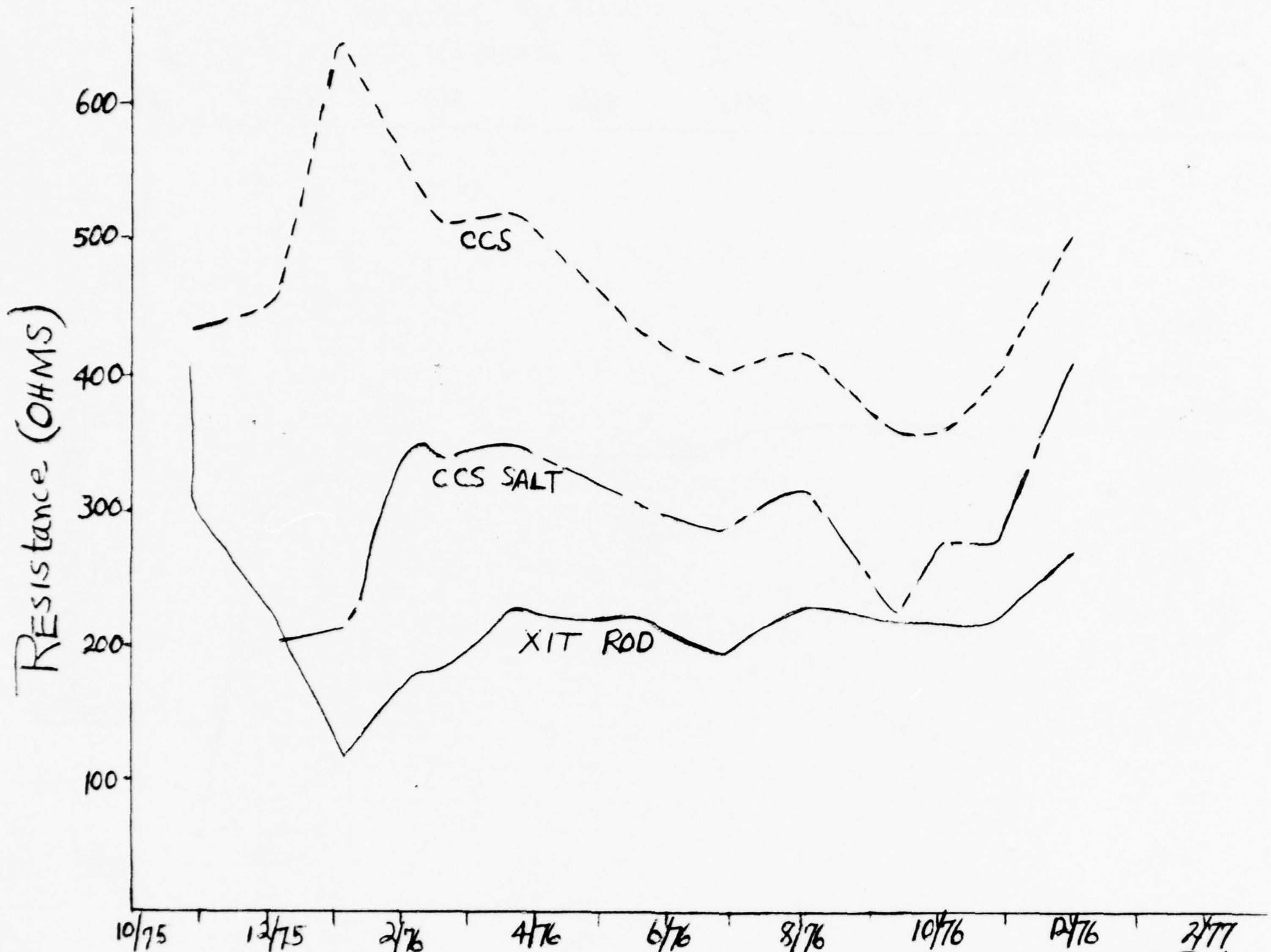


FIG. 2 - Comparative Resistance For Three Types of Grounding Rods Installed At NAFEC, Atlantic City, N. J.

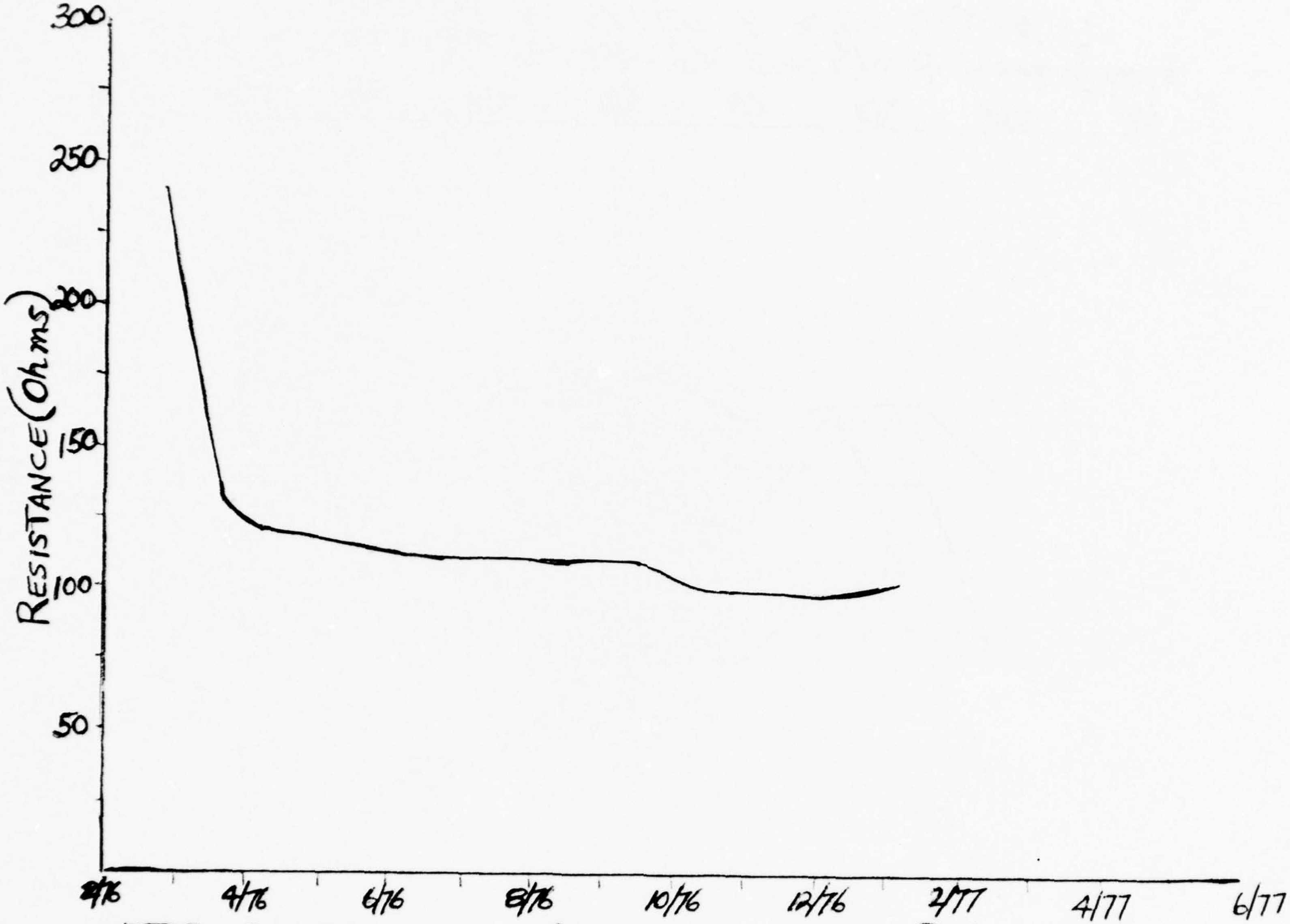


FIG. 3 — Resistance Of A Modified XIT Rod Installed At NAFEC, Atlantic City, N. J.

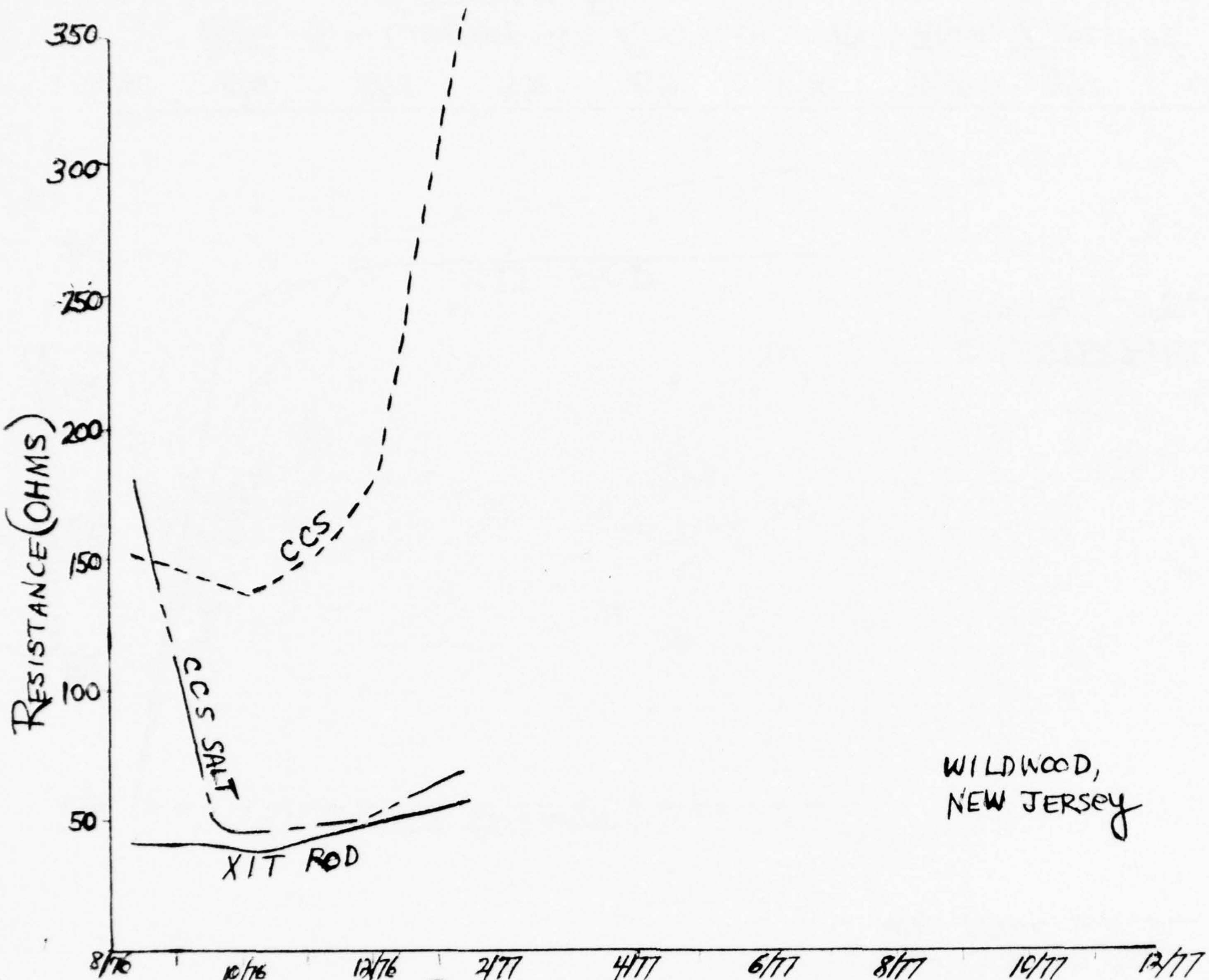


FIG. 4 - Comparative Resistance FOR THREE TYPES OF GROUNDING RODS

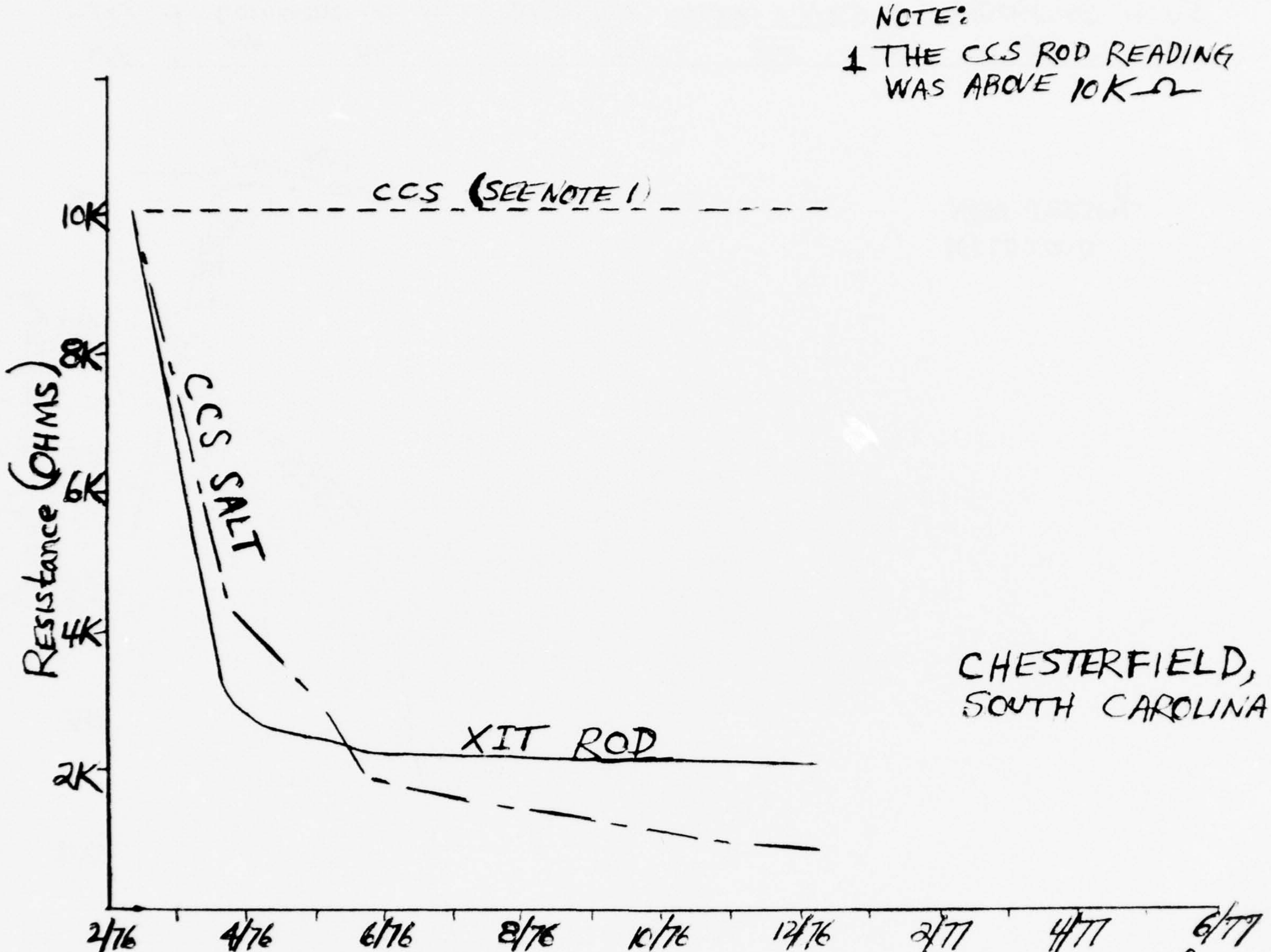


FIG. 5 - Comparative Resistance Of Three Types of Grounding Rods

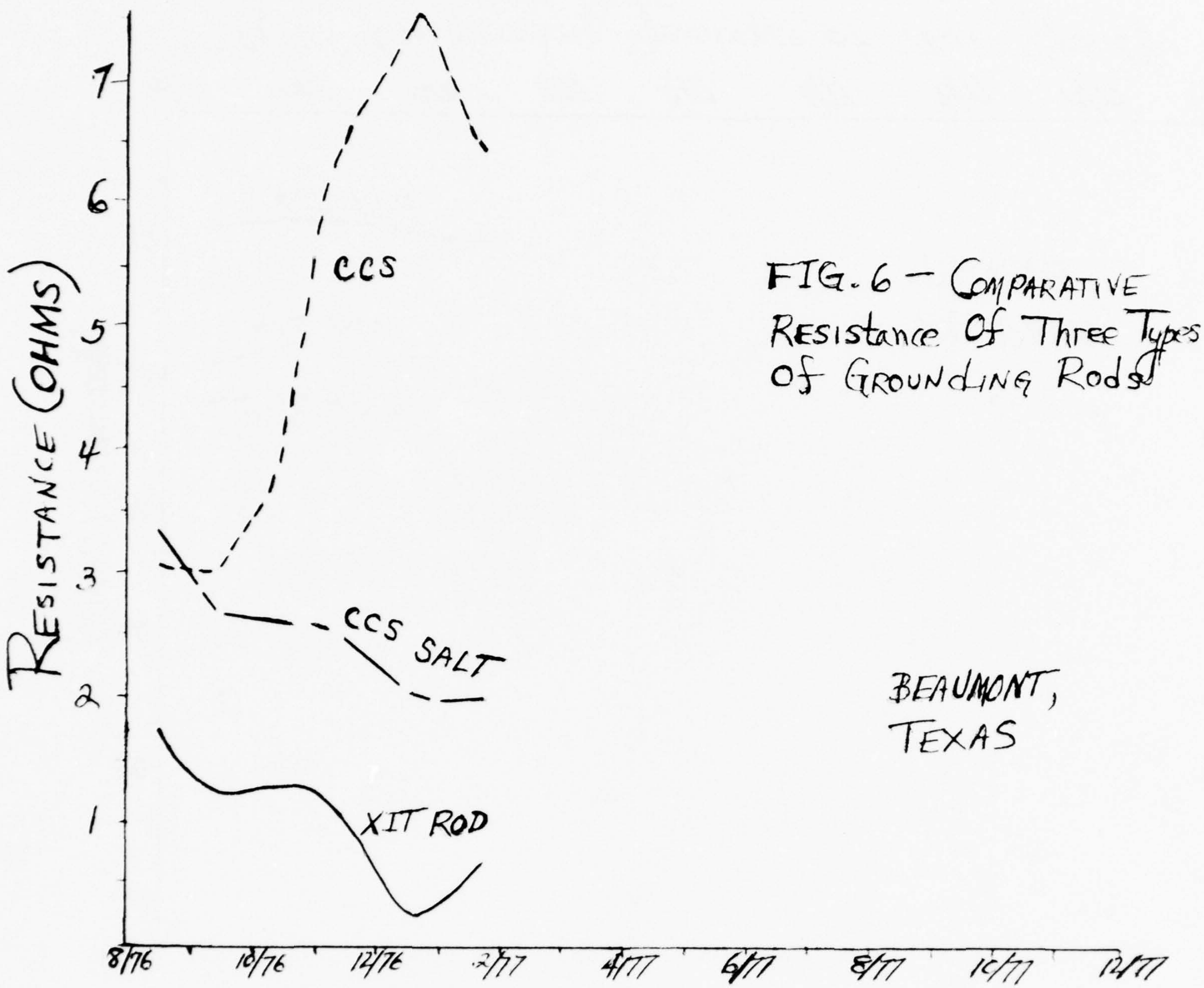


FIG. 6 – COMPARATIVE RESISTANCE OF THREE TYPES OF GROUNDING RODS

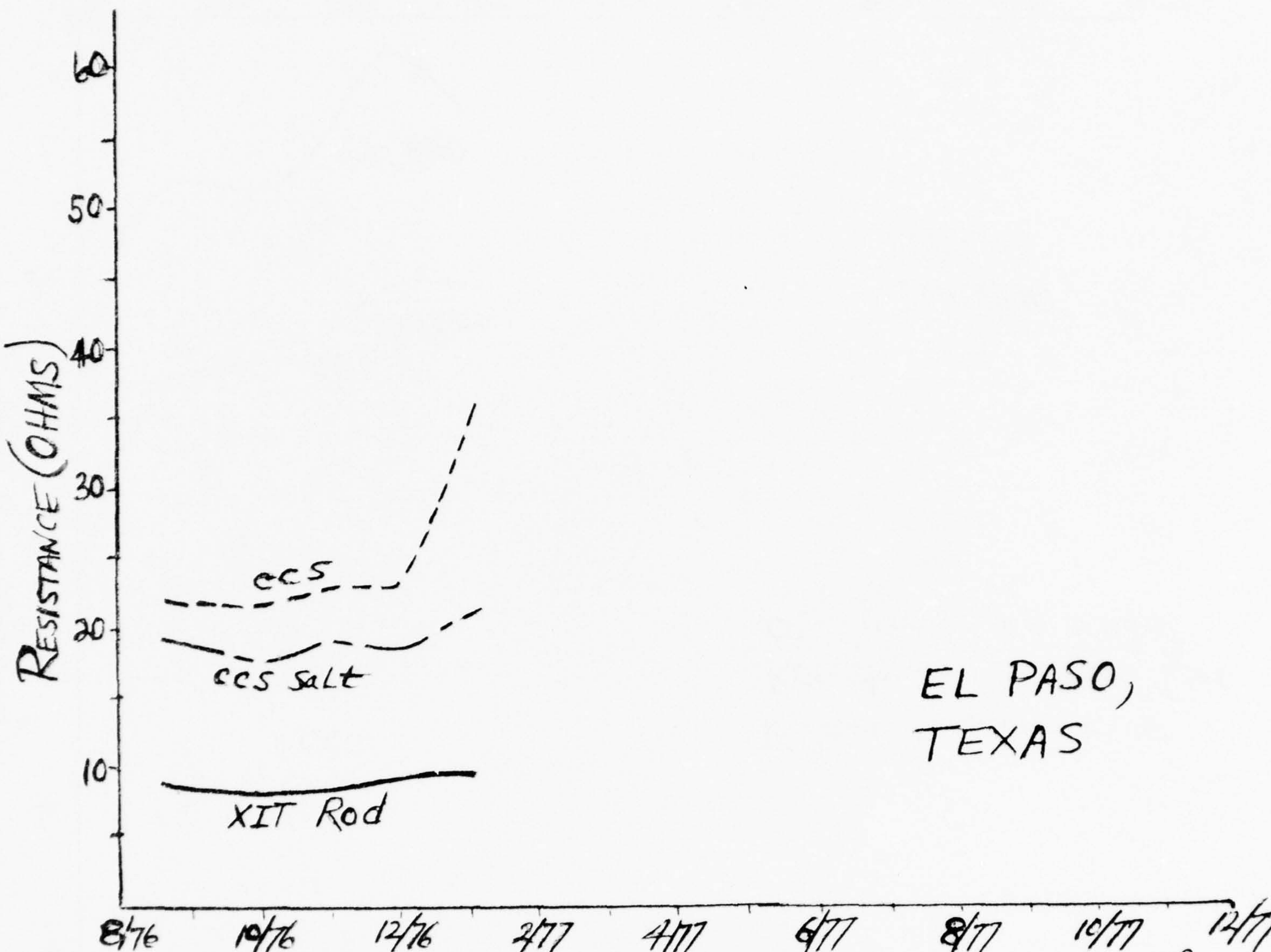


FIG. 7 — Comparative Resistance of Three Types Of GROUNDING Rods

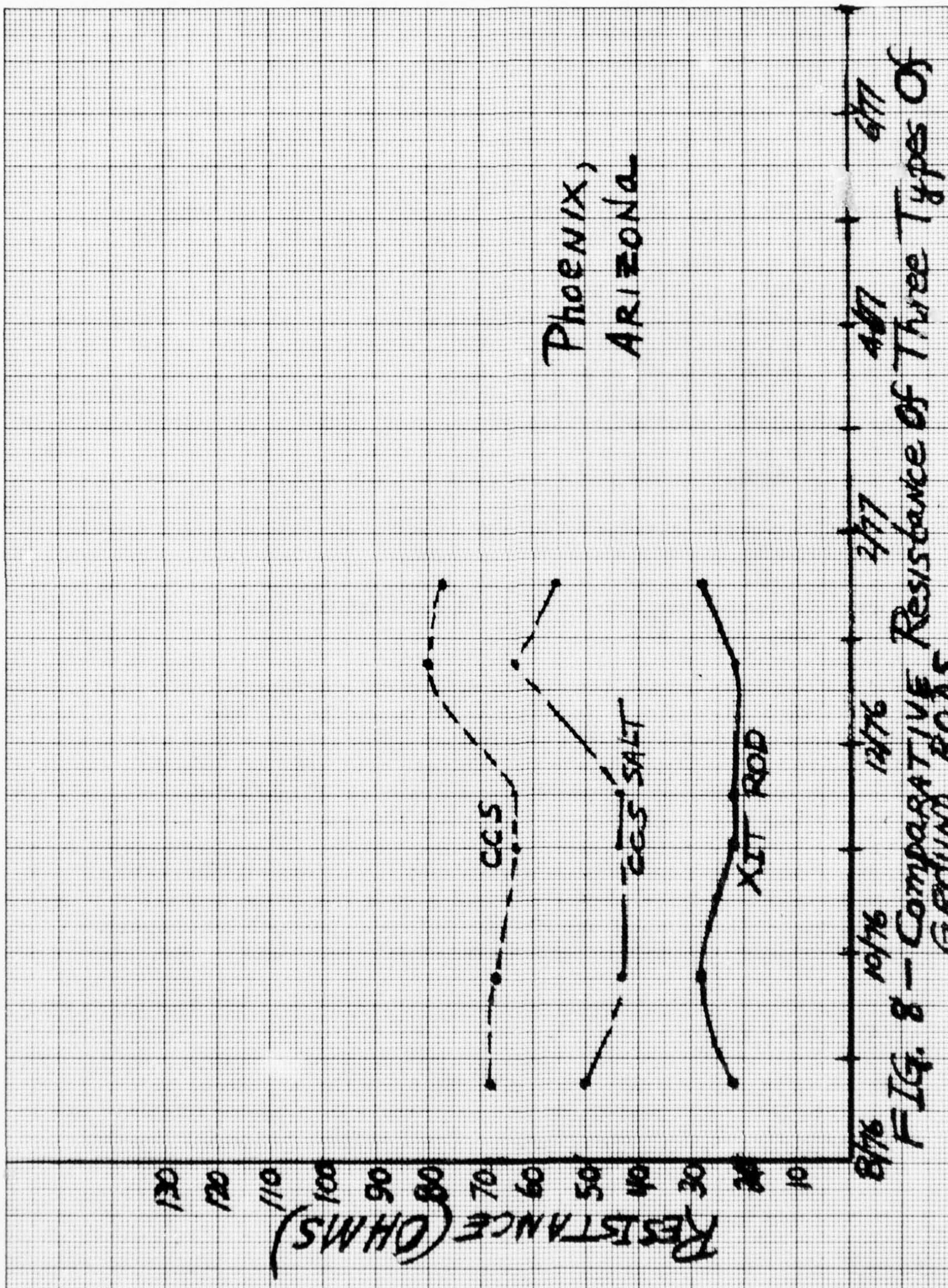


FIG. 8 – Comparative Resistance Of Three Types Of GROUND RODS

Figure 3 is the resistance versus time of an XIT rod with four additional holes drilled on each side about two feet apart along the length of the rod. As can be seen, the ability of this rod to maintain a stabilized ground resistance is very good. The idea to provide additional openings in the rod to allow more chemical solution to flow into the soil along the length of the rod was originated by the author in 1975 and implemented on February 23, 1976. Look at Figure 5 and note that at the Chesterfield, South Carolina site the copper clad steel rod resistance readings are above the maximum scale of 10,000 ohms on the Biddle tester and 3,000 ohms on the Vibroground tester. Additionally, the decrease in resistance when salts are provided to the soil is significant.

Figure 9 shows the XIT rod resistance for five test sites versus time.

Figure 10 shows the copper clad steel (CCS) rod (with salt ring added) resistance for five test sites versus time.

Figure 11 shows the copper clad steel rod resistance for five test sites versus time.

Figure 12 compares the resistance of CCS rods versus XIT rod resistance at five sites. Note that in all cases the XIT rod resistance is one half or less in comparison to a copper clad steel ground rod. The approximate percentages are: NAFEC 50%; El Paso 37%; Phoenix 35%; Wildwood 33%; and Beaumont 4%. For the Chesterfield, S.C. site the percentage is approximately 20%.

In the design of a grounding configuration, it is important to realize that the addition of 2 or 3 CCS grounding rods will not necessarily equal the performance of one XIT ground rod. Later in this paper we will provide an example to demonstrate this.

AIR ROUTE SURVEILLANCE RADAR GROUNDING MEASUREMENTS AND CONFIGURATION

Figure 13 is the grounding configuration for FAA only sites. A goal of five ohms resistance was set. More than twenty sites are to be measured for resistivity values. The FAAinstallation will consist of 17 copper clad steel rods, 10 feet long and 3/4" diameter, interconnected with 4/0 bare wire, about 628 feet in length, buried to a depth of about two feet.

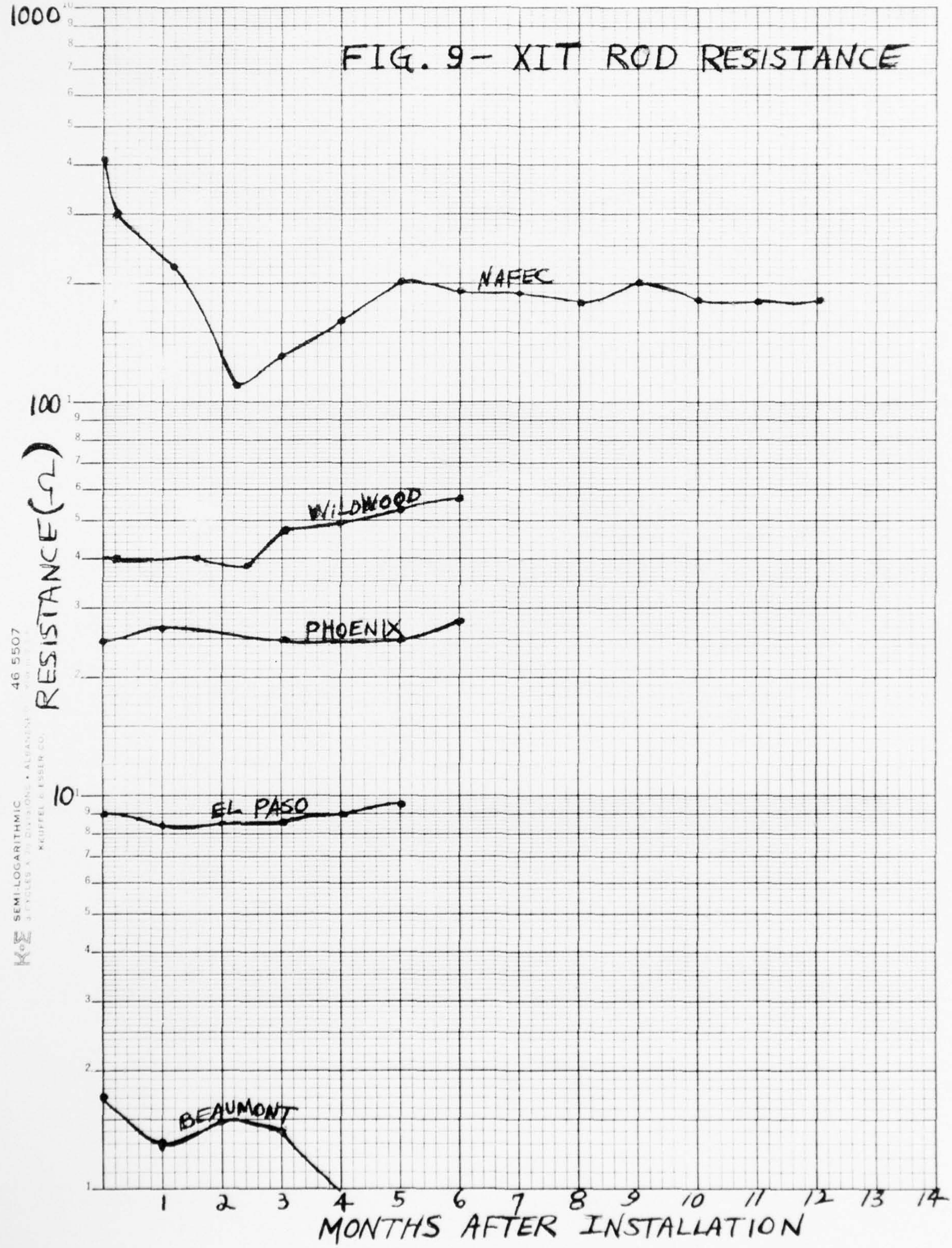


FIG. 9 – XIT ROD RESISTANCE
1000
100
10
RESISTANCE (Ω)
NAFEC
WILDWOOD
PHOENIX
EL PASO
BEAUMONT
1
2
3
4
5
6
7
8
9
10
11
12
13
14
MONTHS AFTER INSTALLATION
K+E SEMI-LOGARITHMIC 46 5507

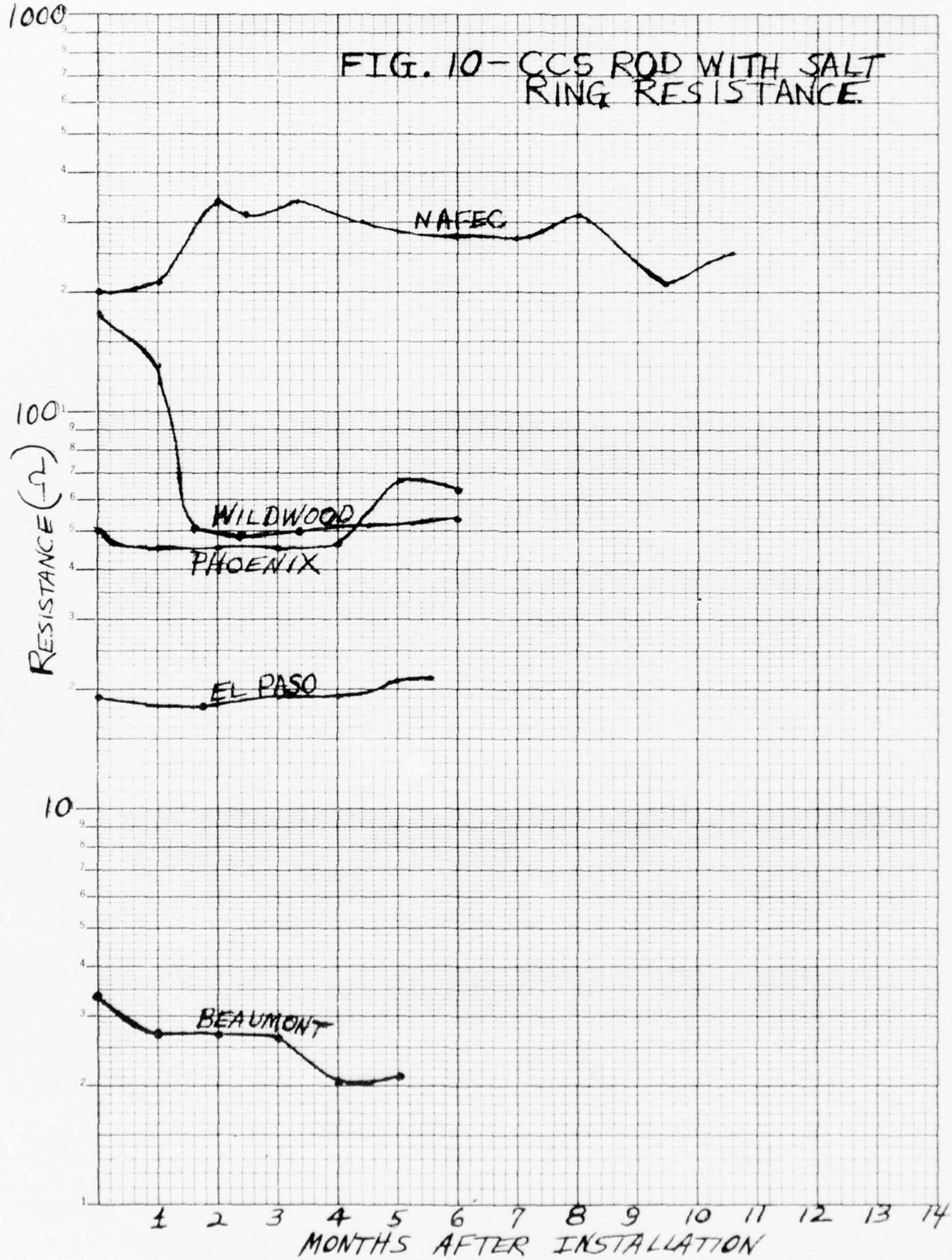


FIG. 10 - CCS ROD WITH SALT RING RESISTANCE
1000
100
10
RESISTANCE (Ω)
NAFEC
WILDWOOD
PHOENIX
EL PASO
BEAUMONT
1 2 3 4 5 6 7 8 9 10 11 12 13 14
MONTHS AFTER INSTALLATION

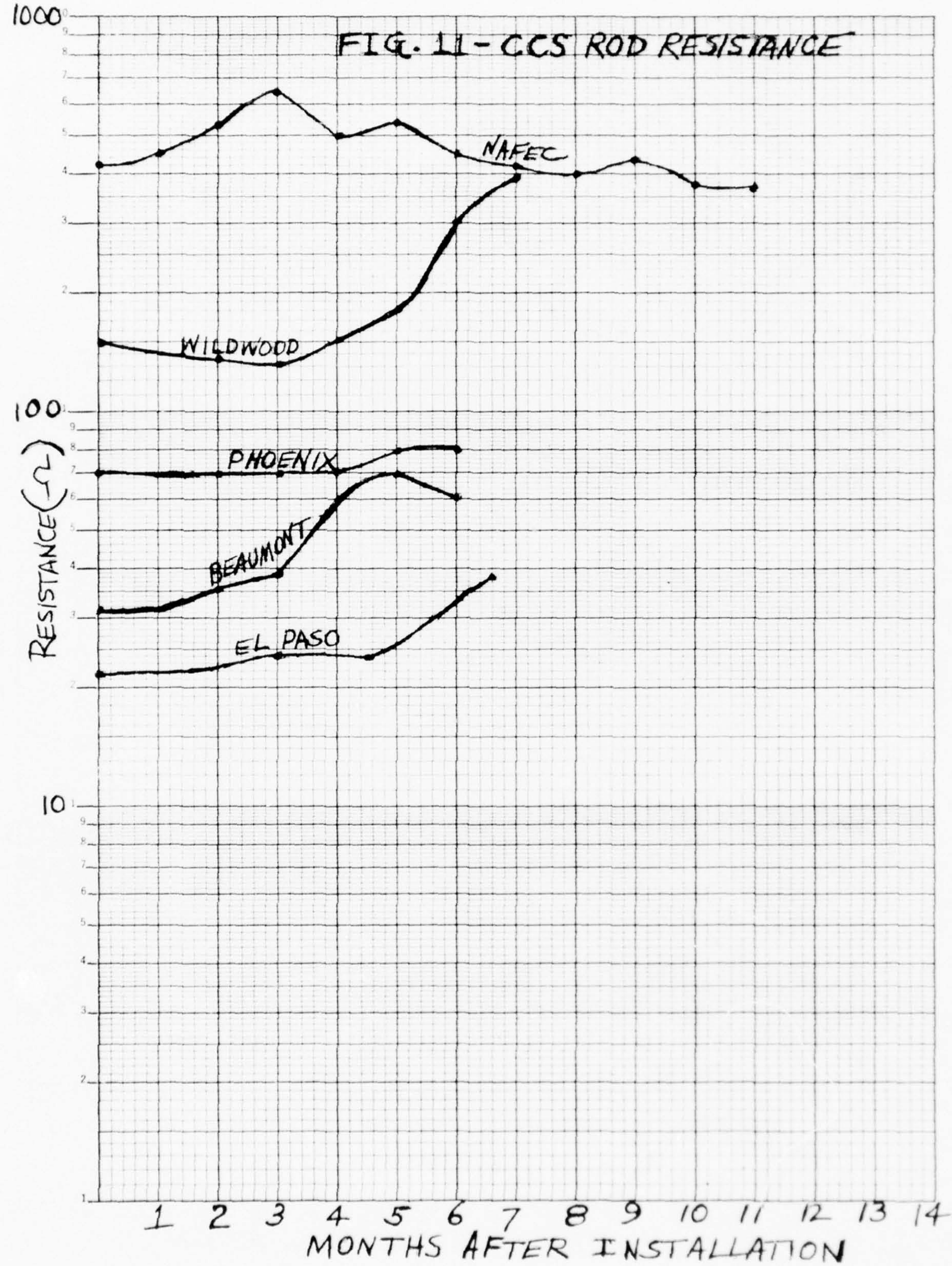


FIG. 11 - CCS ROD RESISTANCE
NAFEC
WILDWOOD
PHOENIX
BEAUMONT
EL PASO
1000
100
10
RESISTANCE (Ω)
1 2 3 4 5 6 7 8 9 10 11 12 13 14
MONTHS AFTER INSTALLATION

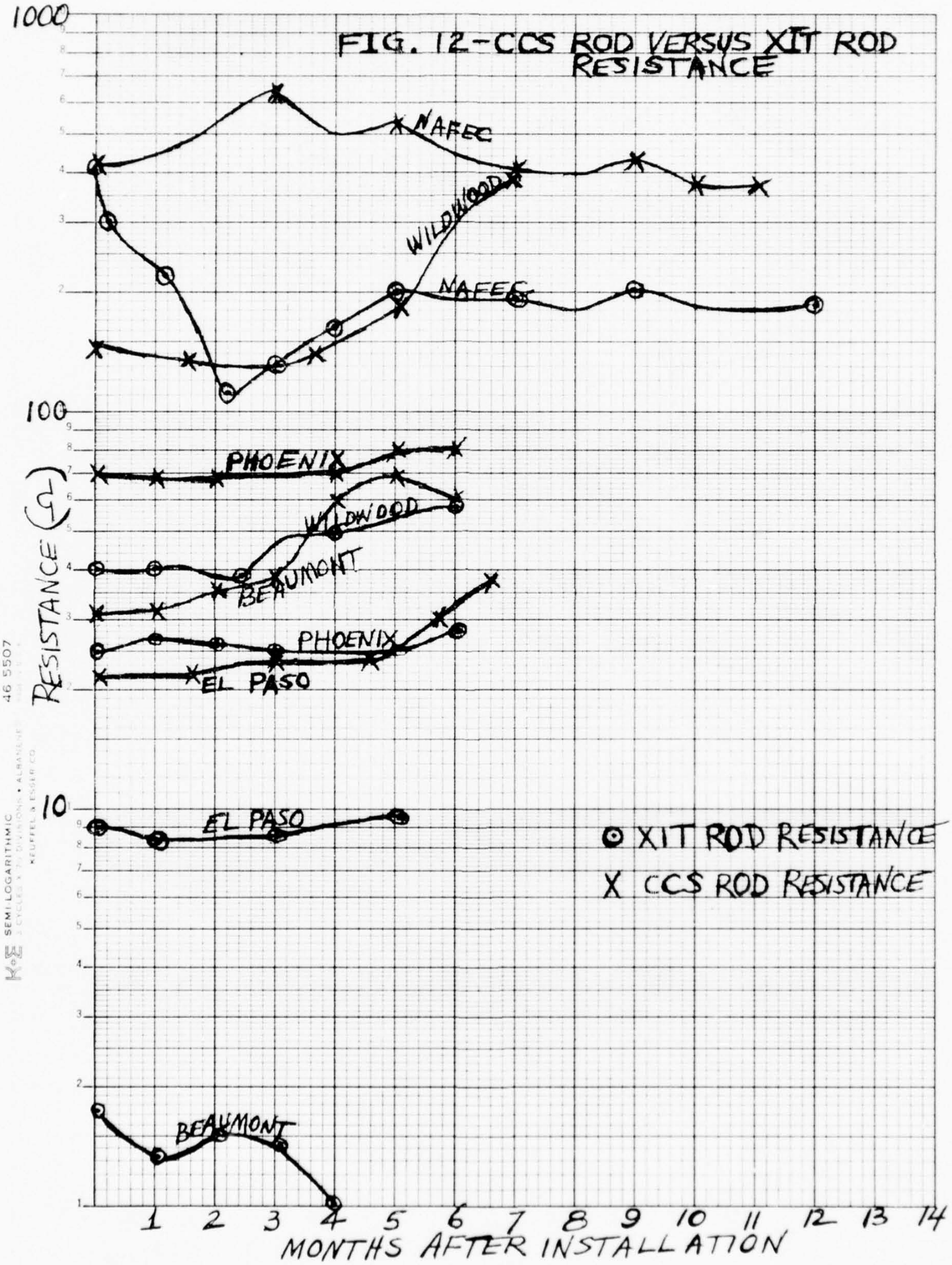
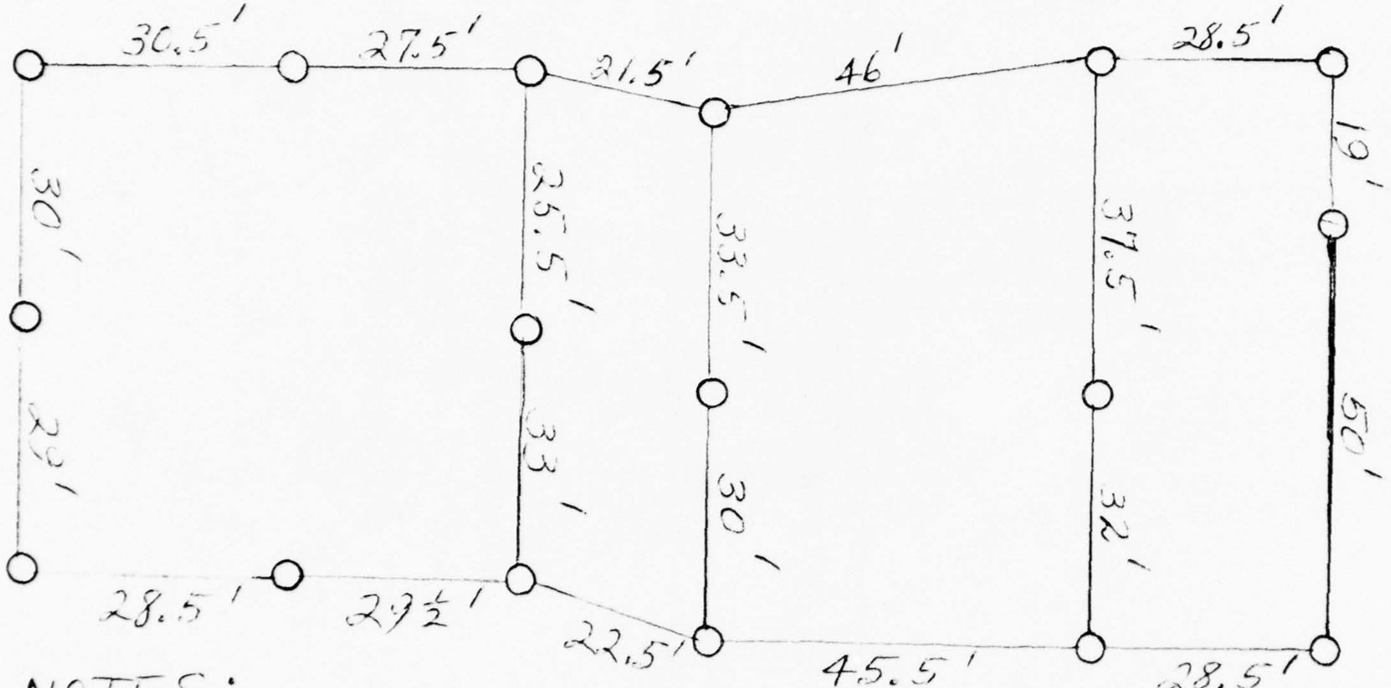


FIG. 12-CCS ROD VERSUS XIT ROD RESISTANCE
1000
100
10
RESISTANCE (Ω)
NAFEC
WILDWOOD
NAFEC
PHOENIX
WILDWOOD
BEAUMONT
PHOENIX
EL PASO
EL PASO
BEAUMONT
⊙ XIT ROD RESISTANCE
X CCS ROD RESISTANCE
1 2 3 4 5 6 7 8 9 10 11 12 13 14
MONTHS AFTER INSTALLATION
K+E SEMI-LOGARITHMIC 46 5507

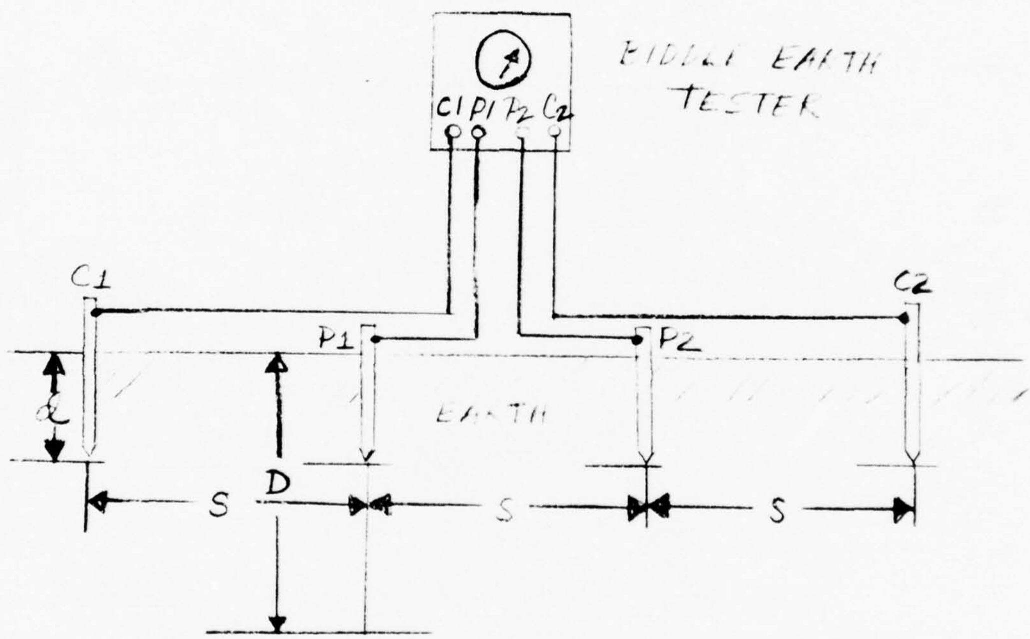
FIG. 13 – GROUNDING CONFIGURATION FOR FAA ARSR-3 SITE



NOTES:

1. GROUND RODS ARE 10' LENGTH, ¾" DIAMETER, CCS
2. INTERCONNECTION WIRE IS BARE COPPER, # 4/0 (.46" DIA.), TOTAL LENGTH IS 628 FEET, BURIED 2 FEET BELOW SURFACE
3. O SYMBOL FOR GROUNDING ROD

FIG. 14 - Earth Resistivity Measurement



S = ELECTRODE SPACING

d = Depth of Penetration $< S/20$

D = Depth At Which Resistivity is determined
$= S$

$\rho = 2\pi S K$ where K is Biddle Earth Tester Reading

Grounding configuration calculations were made using the following formulas:

(1) Resistivity (ρ) = $2\pi s R$ where s is spacing between probes
R is meter reading in ohms
ρ is resistivity

(2) Resistance (one rod) $= \dfrac{\rho}{2\pi \ell}\left(\ln \dfrac{4\ell}{r} - 1\right)$ r is radius of rod
ℓ is length of rod

(3) Resistance (n rods) $= \dfrac{1}{n}\dfrac{\rho}{2\pi \ell}\left(\ln \dfrac{4\ell}{r} - 1 + \dfrac{2\ell}{s}\ln \dfrac{2n}{\pi}\right)$ where s is spacing of rods

(4) Resistance (WIRE) $= \dfrac{\rho}{\pi \ell}\left(\ln \dfrac{2\ell}{(2rd)^{\frac{1}{2}}} - 1\right)$ where d = depth of buried wire
r is radius of wire

(5) Resistance (Total) $= \dfrac{R_W R_R - R_{WR}^2}{R_W + R_R - 2R_{WR}}$ where $R_{WR} = \dfrac{\rho}{\pi \ell_W} \ln \dfrac{2\ell_W}{\ell_R}$

Calculate R_W by Formula (4)
Calculate R_R by Formula (3)

For the FAA grounding configuration considered Formulas (2), (3), (4) and for R_{WR} may be simplified to

$R_1 = K_1\rho$
$R_R = K_R\rho$
$R_W = K_W\rho$
$R_{WR} = K_{WR}\rho$

where K_1, K_R, K_W and K_{WR} are constants shown in Table 4.
ρ is resistivity in meter-ohms.

Since

$$R_T = \frac{R_R R_W - R_{WR}^2}{R_R + R_W - 2R_{WR}}$$

Then

$$R_T = \frac{(K_R\rho)(K_W\rho) - (K_{WR}\rho)^2}{(K_R\rho) + (K_W\rho) - 2K_{WR}\rho}$$

$$= \frac{\rho^2(K_R K_W) - \rho^2(K_{WR})^2}{\rho(K_R + K_W - 2K_{WR})} = \frac{\rho^2(K_R K_W - K_{WR}^2)}{\rho(K_R + K_W - 2K_{WR})}$$

$$= \rho\left(\frac{K_R K_W - K_{WR}^2}{K_R + K_W - 2K_{WR}}\right) = \rho(K_T)$$

where K_T is constant shown in Table 4.

Earth resistivity measurements were made by a NAFEC team employing the four probe technique (Figure 14). Measurements were made for various probe spacings and at several points within the 250' x 250' site location. At some sites the earth resistivity was found to be uniform to a depth of 30 feet or more whereas at other sites the earth resistivity varied with depth.

In Table 5 the Ivor, Virginia ARSR-3 site is shown to have a calculated resistance of 14.07 ohms. This exceeds our resistance goal of five ohms. Let's consider some alternative approaches to reducing the resistance of the grounding configuration at this site. Note from Table 6 the resistance may be reduced to 8.1 ohms by installing 100 foot rods to replace the 10 foot rods. This is equivalent to requiring 153 additional ground rods. Figure 12 indicates the resistance of an XIT rod is less than one rod. Data indicates a range of 4% to 50%. Note that the Ivor site is sand type soil somewhat like the Chesterfield site where data showed a 20% ratio of XIT rod resistance to CCS rod resistance. From Table 5, R_l is 398.215 for CCS ground rod. For the XIT rod, we will assume that R_x is 80 ohms. We will consider the installation of 17 XIT ground rods in place of the 17 CCS rods. The result will be 2.8 ohms.

In any formula for the determination of the resistance to earth, there may be indeterminate factors and too much reliance should not be placed upon the calculated results. For instance, conductors are assumed to be in direct contact with the earth; however, measurements indicate this is not strictly true. Even after grounds have been installed for a long time, the contact resistance at the surface of the conductor may result in a measured resistance value greater than the calculated value. The best way is to measure the grounding resistance configuration after the system has been installed, or make measurements when the grounding system is being installed.

Table 5 shows the various resistance calculations for some of the sites measured to date.

Tabe 6 lists grounding configuration resistance for various ground rod lengths.

CONCLUSIONS

1. XIT rods provide lower resistance grounds than do copper clad steel

rods with or without salt rings and the resistance variability versus time is less. An XIT rod with additional holes drilled along its length results in a lower resistance ground and the resistance variability versus time is less than a standard XIT rod. Measurement data indicates that the resistance of a XIT rod may be from 4% to 50% of the resistance of a copper clad steel ground rod.

2. The copper clad steel rod, salt ring added, provides lower resistance and the resistance variability versus time is less than the copper clad rod.

3. Where earth resistivity exceeds 1000 meter ohms alternative grounding configurations will have to be considered in order to meet a five ohm earth resistance goal for the FAA radar sites. Sites 7, 11, and 9 of Table 5 have such high calculated resistance values that it may be economically infeasible to obtain the resistance goal of five ohms. For these sites, the use of XIT rods should be seriously considered.

TABLE 4 - CONSTANTS FOR GROUND ROD LENGTHS IN *FAA ARSR-3 GROUND CONFIGURATION*

	10'	20'	30'	40'	50'	100'
$K_{\perp}$	.3214	.1788	.126	.0984	.081	.044
K_R	.0238	.01539	.0123	.0107	.0096	.0075
K_W	.01227	.01227	.01227	.01227	.01227	.01227
K_{WR}	.007997	.00685	.00618	.00571	.00534	.00419
K_T	.0113	.0101	.0092	.00836	.00807	.0065

TABLE 5 - CALCULATED RESISTANCE OF FAA ARSR-3 GROUND CONFIGURATION

SITE	METER OHMS	R_{l}	R_{R}	R_{W}	R_{WR}	R_{TOTAL}
IOWA	20.43	6.5662	.486	.2507	.163	.23
MINNESOTA	114.52	36.807	2.726	1.405	1.156	1.39
NORTH DAKOTA	20.30	6.524	.483	.249	.162	.23
MISSISSIPPI	174.52	56.091	4.154	2.14	1.396	1.98
MISSOURI	10.82	3.478	.258	.133	.087	.123
VIRGINIA	1239.0	398.215	29.49	15.2	9.91	14.07
FLORIDA	25892.35	8321.801	616.24	317.7	207.06	294.15
FLORIDA	691.36	222.203	16.45	8.48	5.53	7.85
FLORIDA	6070.92	1951.194	144.49	74.49	48.55	68.97
FLORIDA	1466.02	471.179	34.89	17.99	11.72	16.65
FLORIDA	16326.0	5247.176	388.56	200.32	130.56	185.47

TABLE 6 - GROUNDING CONFIGURATION RESITANCE FOR VARIOUS GROUND ROD LENGTHS

		RESISTANCE TOTAL				
		LENGTH OF GROUND RODS				
SITES	METER-OHM	10 FT	20 FT	30 FT	50 FT	100 FT
IOWA	20.43	.23	.206	.1879	.1629	.1328
MINN	114.52	1.39	1.216	1.13	.913	.749
NORTH DAKOTA	20.30	.23	.207	.1867	.1638	.1319
MISSI-SSIPPI	174.52	1.98	1.78	1.612	1.39	1.14
MISSOURI	10.82	.123	.1093	.0995	.0866	.0703
VIRGINIA	1239.0	14.07	12.6	11.44	9.88	8.1
FLORIDA	25892.35	294.15	263.23	239	206.6	169.3
FLORIDA	691.36	7.85	7.02	6.38	5.514	4.52
FLORIDA	6070.92	68.97	61.72	56.05	48.43	39.66
FLORIDA	1466.02	16.65	14.9	13.53	11.7	9.59
FLORIDA	16326.0	185.47	165.95	150.73	130.25	106.7

REFERENCES

- Grounding Principles and Techniques, Donald T. Jones, April 1976, Report No. FAA-RD-76-104

- Measuring Ground Resistance, Jack L. Hayes, May 1975, Report No. FAA-RD-75-106

- Design and Application of Ground Fields in Power Substations, H.S. Fortson and S. G. Patel, March 1974, Report No. FAA-RD-74-147

- Getting Down to Earth or How to Become Well Grounded in Earth Resistance Testing, J. L. Hayes, March 1974, Report No. FAA-RD-74-147

- Report No. FAA-RD-75-215, Volumes I, II, and III, Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipments and Facilities, December 1975

- Earth Conduction Effects in Transmission System, E. D. Sunde, D. Van Nostrand Co.

SURVEY OF GROUNDING PRACTICES AT MAJOR FAA FACILITIES

by

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ABSTRACT

Three FAA documents presenting the requirements, practices, and survey procedures for grounding, bonding, shielding, and lightning protection at FAA facilities have been developed. Six FAA facilities were surveyed using the criteria and procedures given in these documents. The results of these surveys indicate that with a few important exceptions the grounding, bonding, shielding, and lightning protection systems at these FAA facilities are in good condition and that, for the most part, the survey procedures are adequate. Some of the major deficiencies which need correcting are reviewed in this paper. A few recommendations for corrective actions and the major preliminary conclusions are presented. Also, the areas where the survey procedures need revising and/or expanding are identified. All of the detailed analysis of the survey results are being presented to the FAA in survey reports for these facilities.

SURVEY
OF
GROUNDING PRACTICES AT MAJOR FAA FACILITIES

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1. INTRODUCTION

During the three year period from 1972 to 1975, the Engineering Experiment Station at the Georgia Institute of Technology prepared a facility standard [1], an equipment engineering requirement [2], and a three-volume report (handbook) [3] for FAA. These documents detail the basic theory, principles, practices, and requirements for grounding, bonding, shielding, and lightning protection of new FAA facilities and equipments. The intent of these documents is to permit FAA to improve the grounding, bonding, shielding, and lightning protection of its facilities and equipment. This improvement is sought by establishing a uniform philosophy for new facilities and equipment and by providing some guidance in the upgrading of existing facilities.

After these documents had been prepared, FAA decided to evaluate the procedures in the documents by using them to survey existing FAA facilities. Thus, over the past several months, the Engineering Experiment Station and Kentron-Hawaii, Ltd. of Dallas, Texas, in a joint effort have surveyed several FAA installations and facilities for conformance to the criteria contained in the above documents and for conformance to the National Electrical Code [4].

2. FACILITY LOCATIONS AND TYPES OF TESTS

The surveys were conducted at each of the following systems or facilities:

(a) RCAG in Austell, GA,

(b) ARSR-1 in Smyrna, GA,

(c) Atlanta ARTCC in Hampton, GA,

(d) Jacksonville ARTCC in Hilliard, FL,

(e) ARTS III at the Miami, FL airport, and

(f) ARTS III at the Cincinnati, OH airport.

Based on the inspection and test procedures given in Reference 3, survey procedures for each of the above systems or facilities were developed. For each system or facility, the surveys consisted generally of the following evaluations and/or tests:

(1) Earth electrode system inspection and resistance measurements,

(2) Facility and equipment bond inspections and resistance measurements,

(3) Facility and equipment shield inspections,

(4) Lightning protection system inspections,

(5) Ground network inspections,

(6) Sixty hertz conducted current measurements,

(7) Noise voltage measurements, and

(8) NEC compliance inspections.

3. SURVEY RESULTS

The data obtained from the visual inspections and measurements not only allowed an evaluation of the previously prepared FAA documents but also permitted an examination of the existing conditions and practices in operating systems and facilities. Summaries of the findings for the various inspections and measurements, with the exception of the lightning protection system inspections, are given in the following paragraphs. The results of the lightning protection system surveys are summarized, with emphasis on the ARTCC's, in a paper by Mr. R. S. Smith also published in these proceedings [5].

3.1 Earth Electrode System Surveys

The survey of the earth electrode systems at the RCAG, ARSR-1, and both ARTCC's consisted of a determination of the configuration of the electrode system and several measurements of the resistance to earth. The configurations of the electrode systems were determined from facility drawings and from discussions with site personnel. At each facility, the earth electrode system consists of several separate electrodes that are typically only interconnected by indirect means. For example, at the RCAG one ground rod exists at each of four antenna towers and one ground rod is installed at the equipment building. The only interconnections provided between these five ground rods are by the cable shields from the building to the towers. At the ARTCC's, the earth electrode system consists of water pipes, the power substation ground rods, and a single ground rod at each lightning down conductor on two buildings: the main ARTCC building and the Power Conditioning System (PCS) building. At each building, the individual ground rods and the water pipes are interconnected only through the lightning protection network and incidental contacts with the building's structural steel. Similarly, the only connections between the two buildings are via ac power neutrals and any control/signal cable shields that may exist.

The only exception to these findings of no direct interconnection between the separate earth electrodes was at the ARSR-1. At this facility, one ground rod is installed at each of four corners of the antenna tower, and one ground rod is installed at the equipment building. These ground rods are interconnected with buried conductors routed around the base of the tower and between the building and the tower.

At facilities where direct connections do not exist between the earth electrodes at various facility structures (e.g., antenna towers, equipment buildings, etc.), a lightning strike to one part of the facility could produce large voltage differentials on interconnecting power, signal, and control cables. Such voltage differentials would result in potentially damaging current surges on the interconnecting cables. These current surges would then be coupled to the associated equipments at the end of

the cables to produce possible equipment malfunction or damage. To minimize the magnitude of such voltage differentials and the associated current surges on the interfacing cables, separate electrodes, i.e., ground rods, water pipes, etc., at a facility should be directly interconnected with each other by dedicated conductors.

The resistance to earth at the same four facilities (RCAG, ARSR-1, and two ARTCC's) were measured at several locations and in several directions. In general, the measured resistances were in the following ranges:

(1) Austell RCAG - 22 to 33 ohms,
(2) Smyrna ARSR-1 - 1 to 3 ohms,
(3) Atlanta ARTCC - < 0.5 ohms, and
(4) Jacksonville ARTCC - < 0.5 ohms.

Variations in the value of the earth resistance at a facility are to be expected because of the nonhomogeneity of the soil at that facility. Lightning discharge and fault currents will follow the paths of lowest resistance in the earth. Hence, signal and power cables buried in or parallel to such low resistance paths will be more likely to have potentially damaging voltage surges induced into them. This is one reason why the soil resistivity should be mapped on site before a new electronic facility is built. Then, underground cables can be routed in a manner which will minimize possible pickup from current flow in the earth.

The measured resistances to earth for the larger ARTCC facilities were less than the measured values for the smaller RCAG and ARSR-1 facilities, which is understandable in view of the more extensive earth electrode systems at the larger facilities. Furthermore, the resistance to earth at the RCAG was much higher than at the ARSR-1 even though these two facilities had the same number of ground rods. The higher resistance to earth at the RCAG is likely the result of a high soil resistivity at that location.

3.2 Bond Surveys

The bond surveys consisted of numerous dc resistance measurements between various points on the ground networks in each of the six facilities along with visual inspections of a large sample of the various types of bonds in each facility. The dc resistance measurements revealed that the many parallel paths provided by the ground conductors, conduits, cable trays, etc. in each facility establish a very low resistance path between almost any two points on the ground systems. The majority of the bonds visually inspected were found to be adequate and in good condition; however, several deficiencies were noted. The types of deficiencies which were found during the survey and which can be expected to exist in most any electronic facility are as follows:

(1) Bonds which are loose,
(2) Bonds made with improperly cleaned faying (mating) surfaces,
(3) Soft solder bonds located in probable fault current paths, and
(4) Bonds made between incompatible metals and not sealed against moisture.

To improve the overall condition of the bonds within a facility, all of them should be inspected during regularly scheduled maintenance periods, and the deficiencies that are found should be corrected.

3.3 Shielding Surveys

Both personnel protection and electromagnetic shields associated with each major system in the six facilities were visually inspected. In general, personnel protection shields are correct and are considered adequate. However, a uniform philosophy for the use, application, or installation of electromagnetic shields does not exist even within single systems in a facility. For example, some signal leads are shielded while other comparable signal leads are not shielded. Of the signal leads which are shielded, some of the shields are grounded at the load; other shields are

grounded at the source; other shields are grounded at both ends (and at intermediate points); and still other shields are not grounded at either end. Also, on some low frequency shielded twisted pairs, the shield pig-tails were excessively (as much as 1 to 2 feet) long. Such long pig-tails can be expected to degrade the effectiveness of the shields considerably.

A lack of a uniform shield grounding philosophy in a facility can lead to confusion and problems. A mixed method of shield grounding makes troubleshooting of a system very difficult in the event of noise problems. Consequently, a standardized shield grounding philosophy should be implemented in every system within any particular electronic facility.

3.4 Ground Network Surveys

The ground network evaluations in the surveyed facilities consisted of the inspection and partial mapping of the conductor networks; 60 Hz and RF conducted-current measurements; some noise voltage measurements; and inspections for compliance with the NEC. All of the facilities had equipment ground networks in addition to the NEC safety grounding conductor ("green wire"). The equipment ground networks consist of both dedicated conductors and the incidental conductors provided by cable trays, conduits, etc.

In a few systems, e.g., the automated systems in the ARTCC's, the equipment ground network is supposed to be a single point configuration and is intended to serve as the signal ground. However, signal interfaces and, at one ARTCC, the NEC safety grounding conductors compromise the single-point configuration. This finding illustrates the difficulty associated with attempting to implement and maintain a single-point ground configuration for equipment cabinets and racks. The successful implementation of such a configuration requires that electrical isolation be maintained between the equipment housings and metal elements of the facility such as the structural steel, conduits, and cable trays. Other experience has also shown that such isolation is indeed difficult to maintain [6], [7].

In many of the facilities, the 60 Hz current measurements reveal several amperes of current flowing in the ground networks. In some instances these stray 60 Hz currents could be traced to NEC violations such as a reversal of the neutral (identified) conductor and the safety (grounding) conductor. For example, at the Jacksonville ARTCC, 0.4 amp of 60 Hz current was measured in the equipment ground conductor to one row of position consoles in the control room. The source of this current was traced to the common logic power supply by measuring the current unbalance (2.5 amps) in the ac power cord to this equipment. This power cord contained the phase, neutral, and safety conductors and, hence, the net current flow measured for all conductors should have been zero. The site personnel inspected this equipment and found that its neutral and safety wires were reversed. The deficiency was corrected, and further current measurements on both the power cord and the console ground conductor revealed zero amperes.

Similarly, several amperes of 60 Hz current were measured on various equipment ground conductors at the Smyrna ARSR-1. Inspections of the ac distribution panels showed that the neutrals were grounded in several of these panels. (All of the distribution panels in a facility should be inspected to insure that the neutrals are not inadvertently grounded.) Further investigations and review of equipment manuals at this facility revealed that the ac neutral was also grounded in almost all the equipments. This equipment has been designed by the manufacturer to have the ac neutral grounded internal to the equipment; therefore, to isolate the neutral would require major rewiring and possibly redesign of all such equipment in this facility. In this facility where the majority of the equipments are designed with the neutral grounded, it is not considered cost effective to redesign or rewire the equipment as long as noise problems are not traceable to stray 60 Hz ground currents. However, should noise problems arise in the future, grounded neutrals in equipments should be considered as a possible cause of such problems.

For some other stray 60 Hz currents on equipment ground networks, the source could not be determined during the surveys. For example, small 60 Hz currents (less 0.3 amps) were measured on the ground networks for other rows of position consoles in the control room at the Jacksonville ARTCC. When the current unbalance was measured on the power cords to several Flight Strip Printers (FSP), these currents were found to be approximately 1 amp. Also, further inspection revealed that these current unbalances increased up to 2.5 amps when the case of the FSP (which is normally insulated by a rubber pad) was grounded to the position console frame. However, a wiring deficiency could not be located when one of the FSP's was disassembled. The reason for unbalanced current in the power cords and, hence, the stray current in the equipment ground network was not determined.

During these surveys, differential voltage and conducted RF current measurements were performed on the "signal ground" systems at some of the facilities. However, several measurement problems were encountered. First, a true differential-input oscilloscope was not available. Thus, stray pickup on the long test leads required to perform measurements between widely separated points limited the ability to determine the magnitude of the actual noise being measured. The second problem was the determination of the measurement points. Lack of evidence on the existence of present noise problems made this determination ambiguous. The final problem was the inability to shut down operational equipment such that the source of any existing noise could be isolated. Therefore, due to these problems, the data produced by these measurements is inconclusive.

The remaining parts of the grounding survey at each facility consisted of a review of facility drawings and a visual inspection to determine compliance with the requirements of the NEC. Concurrent with the visual inspections, 60 Hz current measurements were made on selected phase, neutral, and safety grounding conductors. These current measurements were made in addition to the current measurements described in the above paragraph. The majority of the discrepancies found were of the following types:

(1) Fault current paths (safety grounding conductors) back to the power panels, switchgear, transformers, etc. which are not routed with the phase and neutral conductors;

(2) Phase, neutral, and safety grounding conductors that are not properly color coded;

(3) Neutral conductors that are grounded on the load side of the main disconnect switch, e.g., in distribution panels or in equipments; and

(4) Neutral and safety grounding conductors which have been reversed.

These types of deficiencies are common in electronic facilities; such deficiencies can introduce 60 Hz noise into ground networks and some of them may produce possible personnel shock hazards. For these reasons, comprehensive NEC inspections should be performed in all facilities and all identified deficiencies should be corrected.

4. CONCLUSIONS

The following conclusions are based on a detailed analysis of the data obtained during the surveys of the seven FAA facilities and, for the most part, are expected to apply to any complex electronic facility:

(1) The general grounding, bonding, shielding, and lightning protection practices employed at the various facilities surveyed were good. In most respects, these practices were found to be in accordance with the criteria and recommendations set forth in References 1, 2, and 3.

(2) The resistance to earth was lowest at the larger facilities, i.e., the ARTCC's, because of the more extensive earth electrode systems at these facilities. However, the earth electrode system at each facility needs some improvement to minimize the possibility of equipment/system damage resulting

from lightning strokes. In particular, facilities which have a separate ground rod at each down conductor should have a buried counterpoise around the facility. This counterpoise should interconnect each ground rod and should, also, be connected to the structural steel and ground networks in the facility.

(3) In general, the bonds at each facility were in good condition and considered adequate to serve their intended functions. However, a few discrepancies/deficiencies were found such as bonds that were loose, bonds which had been made between improperly cleaned surfaces, and bonds that had been made with soft solder located in likely fault current paths. During routine maintenance at all facilities, bonds should be inspected and any deficiencies which are found should be corrected.

(4) The facility/equipment ground networks within the surveyed facilities are generally considered adequate; however, in most locations independent signal ground systems were not found.

(5) The shielding practices, especially shield terminations, in the six facilities which were surveyed were not uniform even within single systems. Some low frequency cable shields were terminated at the sources; some shields were terminated at the loads; other shields were not terminated; and still other low frequency cables were unshielded. A standardized philosophy of cable shield terminations in FAA systems should be implemented.

(6) More survey work should be performed in the area of interference problems and their relationship to signal grounding and shield terminations. Also interference measurement techniques such as the differential noise measurements

should be tested and procedures for determining the measurement points and for interpreting the measured results should be developed.

(7) In general, the inspection procedures contained in Reference 3 (the Handbook) were found to be adequate. A few deficiencies in the procedures were found, and appropriate changes are now being formulated.

5. REFERENCES

1. "Buildings and Structures, Grounding, Bonding, and Shielding Practices, General Requirements," Federal Aviation Administration Standard FAA-ER-350-024, 31 July 1973.

2. "Electronic Equipments, Grounding, Bonding, and Shielding Practices, General Requirements," Federal Aviation Administration Engineering Requirement/Specification FAA-ER-350-023, 20 February 1975.

3. H. W. Denny, et. al., "Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipments and Facilities," FAA-RD-75-215, (3 Volumes), Federal Aviation Administration, Washington, DC, December 1975.

4. National Electrical Code 1975, NFPA 70, National Fire Protection Association, Boston, MA.

5. R. S. Smith, "Lightning Protection for Facilities Housing Electronic Equipment," Proceedings of the 1977 FAA/FIT Workshop on Grounding and Lightning Protection, Melbourne, FL, April 1977.

6. "Final Report on the Development of Bonding and Grounding Criteria for John F. Kennedy Space Center," WDL-TR4202 (3 Volumes), Contract NAS10-6879, Philco Ford Corp., Palo Alto, CA, 30 June 1970.

7. D. R. Lightner and J. C. Toler, "Implementation of Bonding Practices in Existing Structures," Proceedings of the Eighth Tri-Service Conference on Electromagnetic Compatibility, Chicago, IL, October 1962.

A SYSTEM GROUNDING APPROACH FOR HIGH SPEED DIGITAL COMPUTER GENERATED IMAGE (CGI) SIMULATION DEVICES/TRAINERS

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ABSTRACT

The technology involved in the design and development of complex CGI pilot and radar operator training devices involves very sensitive electronic subsystems, modules and circuits. The end-item compatibility of the complex trainer requires grounding design techniques and precautions from site/facility grounding down through circuit board grounding detail. This paper describes the grounding design-in of a typical CGI simulator/trainer involving electrical power, safety, computer floor, cabinets and racks, signal grounding, logic backplanes, interface circuits, and circuit board grounding rules.

INTRODUCTION

The technology involved in the design and development of a complex Computer Generated Image (CGI) pilot and radar operator training device involves very sensitive electronic subsystems, modules, and circuits. The typical CGI system consists of an Image Generator supported by commercial data processing equipment such as discs, tapes, transports, controllers, and line printers performing as a system to feed video signal to optical displays such as light valves or cathode ray tubes.

The CGI system's Image Generator, often called a special purpose computer, produces the video images which are then processed onto the video display devices, such as the CRTs. Image Generator logic rates typically are as high as 40 megahertz with switching thresholds of approximately one volt. The Image Generator must interface with the commercial electrical power and display equipment to present visuals to students. The result is a physically large system that is potentially susceptible to ground noise and circulating self generated and facility produced ground loops. Figure 1 illustrates the Device 2B-35 layout now in operation at Chase Field in Beeville, Texas. Figure 2 illustrates the device 1D-23 in operation at Pensacola, Florida. Interfering sources which could propagate through the sensitive electronic equipment range from lightning, power company and facility electrical transients, and nearby RF equipment as well as self generated sweep circuit, card reader activation or power supply switching currents. The overall trainer ground philosophy must mix a single point grounding approach to eliminate ground loops with a multipoint grounding approach to provide the RF characteristics required for these low level high bandwidth logic rates. This paper discusses how these grounding problems have been solved on several General Electric training devices.

ELECTRICAL GROUNDING

The CGI trainer is usually supplied 120/208 ± 10%, 60 Hz ± 5%, 3 phase, 4 wire Y power from a customer provided power delta to wye step down transformer. The power quality as defined does not usually include transients and spikes produced by power grid switching, lightning, or other industrial users. Our experience and measurements by other researchers have indicated that power line transients and spikes often exceed 1000 volts, especially during nearby thunderstorm activity. The approach that has been taken on recent trainers is to dedicate a transformer solely to the trainer electronics with the transformer providing an electrostatic shield between windings. This approach offers:

a. The separate transformer reduces facility/site harmonic distortion and noise.

b. Provides a separate power neutral, thus a separate single ground point for the trainer while still complying with facility safety requirements.

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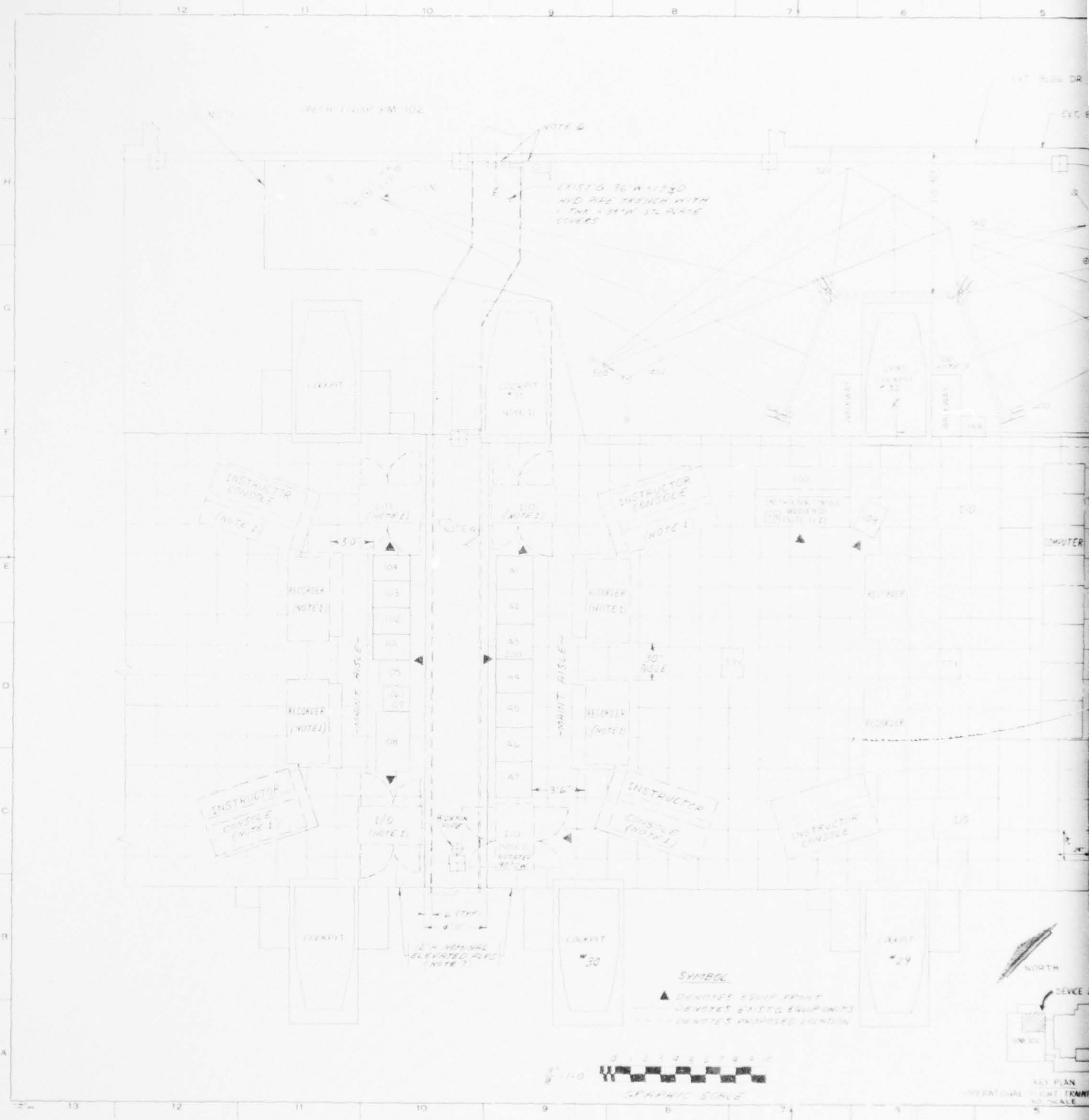

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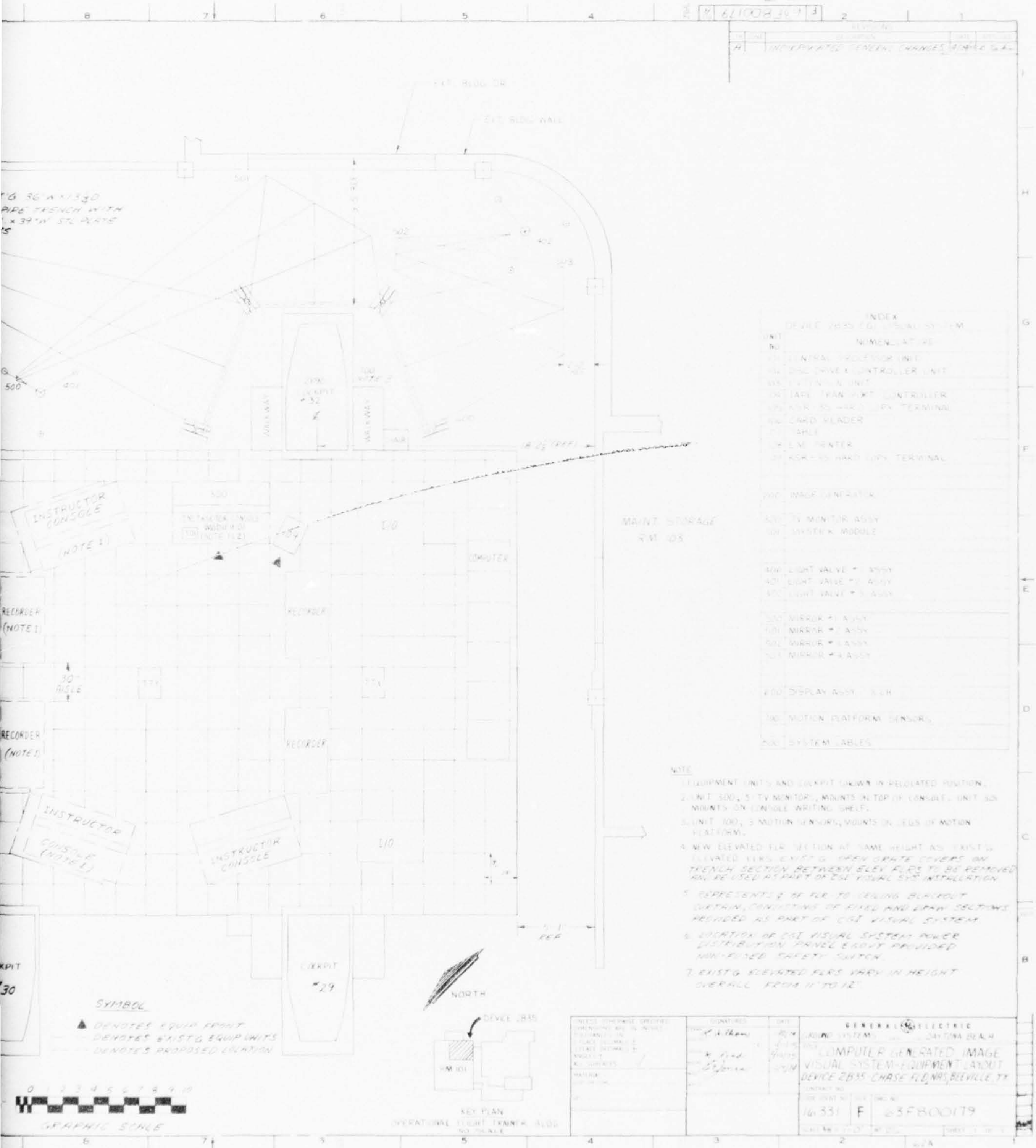

Figure 1. Device 2B35 Layout

Figure 2a. Device 1D23 Logic Image Generator

Figure 2b. Device 1D23 Visuals and Instructors Units

c. Sharp spikes on the primary due to lightning or other sources are reduced from over 1000 volts to less than 100 volts. The shield adds approximately 10% to the cost of the transformer and is available from commercial suppliers.

TRANSFORMER GROUNDING

The facility Δ to Y power transformer is usually grounded as follows:

a. The center tap (A) of the 3 phase delta is referenced to earth/building ground at a near-by convenient but solid earth ground location. This may be a buried cable or grid system which is used to tie building steel and columns to earth or a ground well is sometimes used for this purpose. The ground riser (transformer to grid connection) conductor is sized to handle fault currents, usually an AWG #2/0.

b. The electrostatic shield terminal is connected to the neutral stud/tap, this decouples spikes and noise directly to earth ground.

c. The metal case of the transformer is grounded to the neutral tap of the secondary for safety purposes. The transformer three phase output power is always accompanied by the neutral (white) and a safety ground conductor (green). Conduit may be aluminum or steel and is secured to the transformer case and the safety switch.

FACILITY SAFETY SWITCH

A facility provided power safety switch usually follows the transformer. This box allows complete disconnection of the trainer. The neutral line is carried through this box floating. The box is grounded to the green wire of the feed cable. The input and output conduit should be continuous and secured to the safety switch box and follow-on trainer power panel board.

TRAINER POWER PANEL BOARD

GROUNDING

The panel board (chassis) is grounded to the green wire safety ground coming from the safety switch. Neutral is not tied to the board at this location. The feed-in conduit is secured to the panel board. Output distribution conduits are insulated from the panel board via polyvinyl chloride (PVC) fittings to prevent power ground currents from flowing through the conduit path. These output conduits end up being grounded to the signal ground system, usually an elevated computer floor, as discussed further herein. The green wire distribution system continues on with the 3 phase feeder lines as discussed below.

ARC/TRANSIENT SUPPRESSION

Transients caused by deactivating individual loads at the circuit breaker could reflect large spikes onto sensitive loads on the same phase. These transients are

suppressed at the panel board with GE Power Metal Oxide Varistors (MOVS) from each phase to neutral (see Figure 3). The V150PA20 power MOVS clip the voltage above 250 volts peak. The V150PA20 is rated at 20 joules. 20 joules is equivalent to 20 watt X seconds or 20 megawatt X microseconds. The 20 joule suppressor will survive a 2000 amp transient for 40 microseconds.

ELECTRICAL LOADS

Electrical loads such as the Image Generator enclosures use 120/208 volts, 3 phase power. Other loads use single phase, either 120 volts or 208 volts line to line. Loads are allocated such that phases are balanced. Conduits feeding these loads are isolated at the panel board and routed to the load's outlet box directly. Where these conduits must come in contact with building columns, plumbing or any other metal work which could introduce circulating currents, the conduit must be insulated by taping or other means. Load outlet boxes, usually lying beneath the enclosure under the computer floor are jumper-connected to the computer floor with an AWG # 8 or 10 conductor to a nearby computer floor support pedestal. The green wire safety ground system which originated at the source transformer is connected to the receptacle outlet safety ground terminal or lug. The safety ground is thus continuous and is compliant with the National Electrical Code without introducing ground loops.

NOTE

> Where either the facility safety switch or the panel board must be bolted to a steel column or other metallic member which is referenced to other than the transformer neutral reference ground system, the trainer's green wire ground should be isolated in these boxes. A second or third green wire ground is used in the feeder cable to connect these boxes directly back to the transformer in such instances. Another precaution that has been satisfactorily used is to mount the panel board and safety switch on insulating material such as plywood to ensure isolation from undesirable ground potentials.

ENCLOSURE SAFETY GROUND

The power pigtail or cord provides the enclosures with the necessary safety ground. The green wire system is continuous on up into the enclosure power distribution panel and is tied to the main chassis as well as any removable or drawer mounted assemblies.

POWER SUPPLY GROUNDING

General Electric training devices use both 3 phase and single phase power supplies. All power supplies in use have been qualified for noise rejection characteristics per MIL-STD-461 CS-06 and CS-01. Other self imposed tests are performed to ensure that the power supply will isolate trainer produced ripple, such as caused by the Image Generator's SCR switching regulator supplies. The 3 phase SCR power supplies, although notoriously noisy, have been successfully integrated into the most recent Image

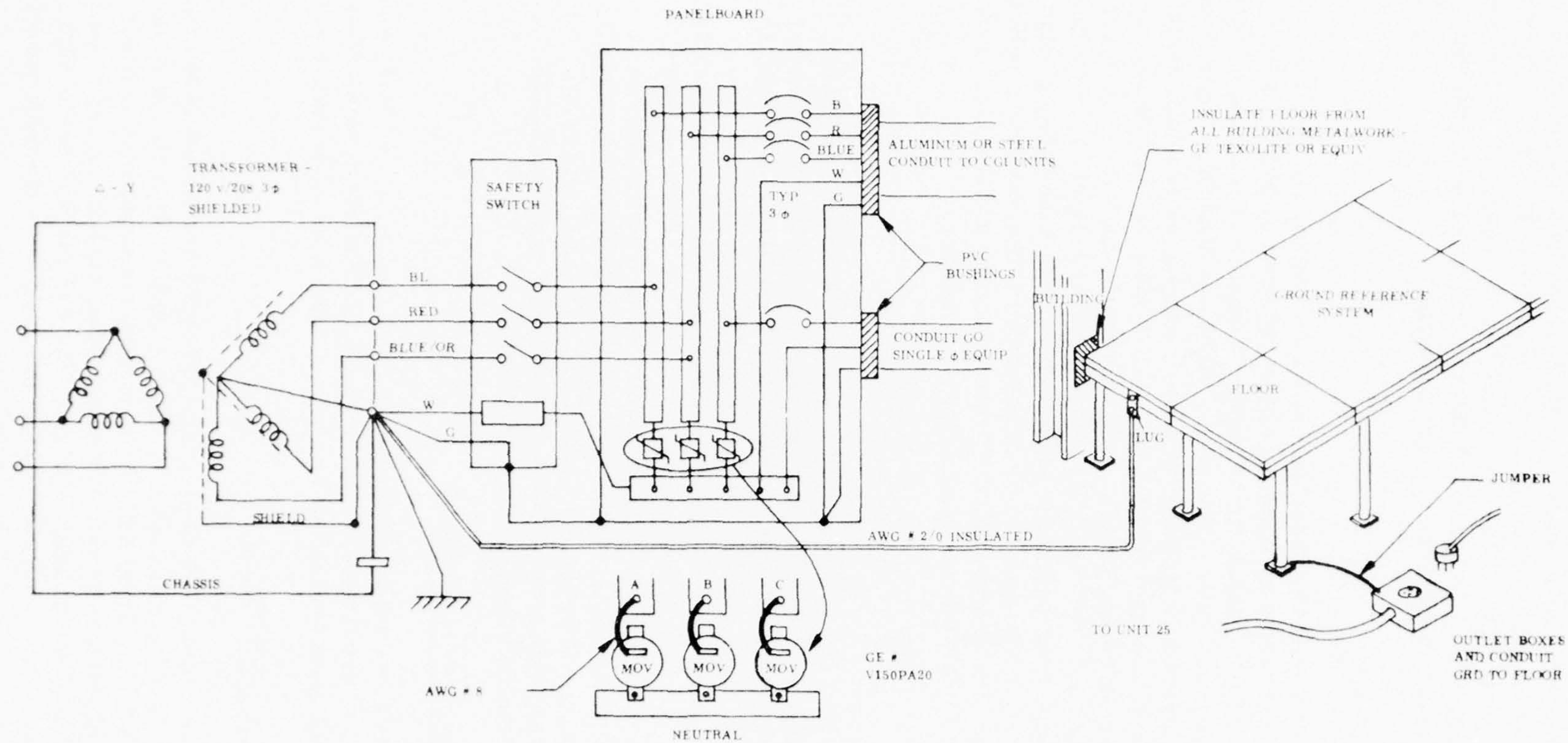

Figure 3. Trainer System Grounding

Generator designs. A single 5 volt DC 500 amp SCR supply per enclosure replaces 5 switching regulator supplies and a power control panel previously used. The single supply concept offers considerable advantages in the reliability, electrical design, and cost areas, however, certain power and grounding design precautions are required to minimize self-generated noise problems due to the supplies. These are:

a. Each enclosure is on a separate feeder circuit routed directly back to the panel board circuit breaker.

b. The 3 phase feeder is not used for other single phase equipment or blowers within the enclosure; these use a separate single phase feeder line.

c. The power supplies 5.0 volt DC output return which becomes the IG signal ground, is bussed up into the logic backplanes, both top and bottom ground busses, to minimize IR drop due to the 400 amps typical logic load.

SIGNAL GROUNDING

A signal grounding concept has been utilized in recent trainers which allows all enclosures within the device to be essentially single point grounded. This prevents noise currents from flowing through the low level signal paths and thus causing
The signal point reference for these enclosures is the computer floor's metallic structure on which the trainer system is mounted. Utilization of the computer floor (the raised metal floor consisting of risers, stringers, and removable panels) was originated at the Naval Device Training Center (NDTC) in Orlando and has very specific advantages over an ordinary cable grid ground system. These are:

a. Single Point Grounding. The floor is installed in the facility such that it is isolated from all other electrical equipment or building grounds. Special precautions such as installing vinyl floor tile, tape, or other insulating material where the metal work may touch other building grounds are used during installation. A test is performed to ensure that the floor is isolated prior to installation of the trainer equipment. This installation and test procedure ensures us that the floor will be a dedicated trainer single point ground when complete. The isolated floor becomes single point grounded directly back to the transformer neutral via an insulated AWG # 2/0.

b. Multipoint Grounding. The floor also offers us the advantages of multipoint grounding. The floor's risers, stringers, and panels are specified to be either aluminum or galvanized steel. Assembly hardware and procedures are closely specified to ensure that interfacing metals are compatible and will provide long term low contact impedance. Figure 4 represents the requirements of this hardware. Thus, when the floor members become assembled the floor looks like a continuous ground plane for signal cabling and even to outside noise sources.

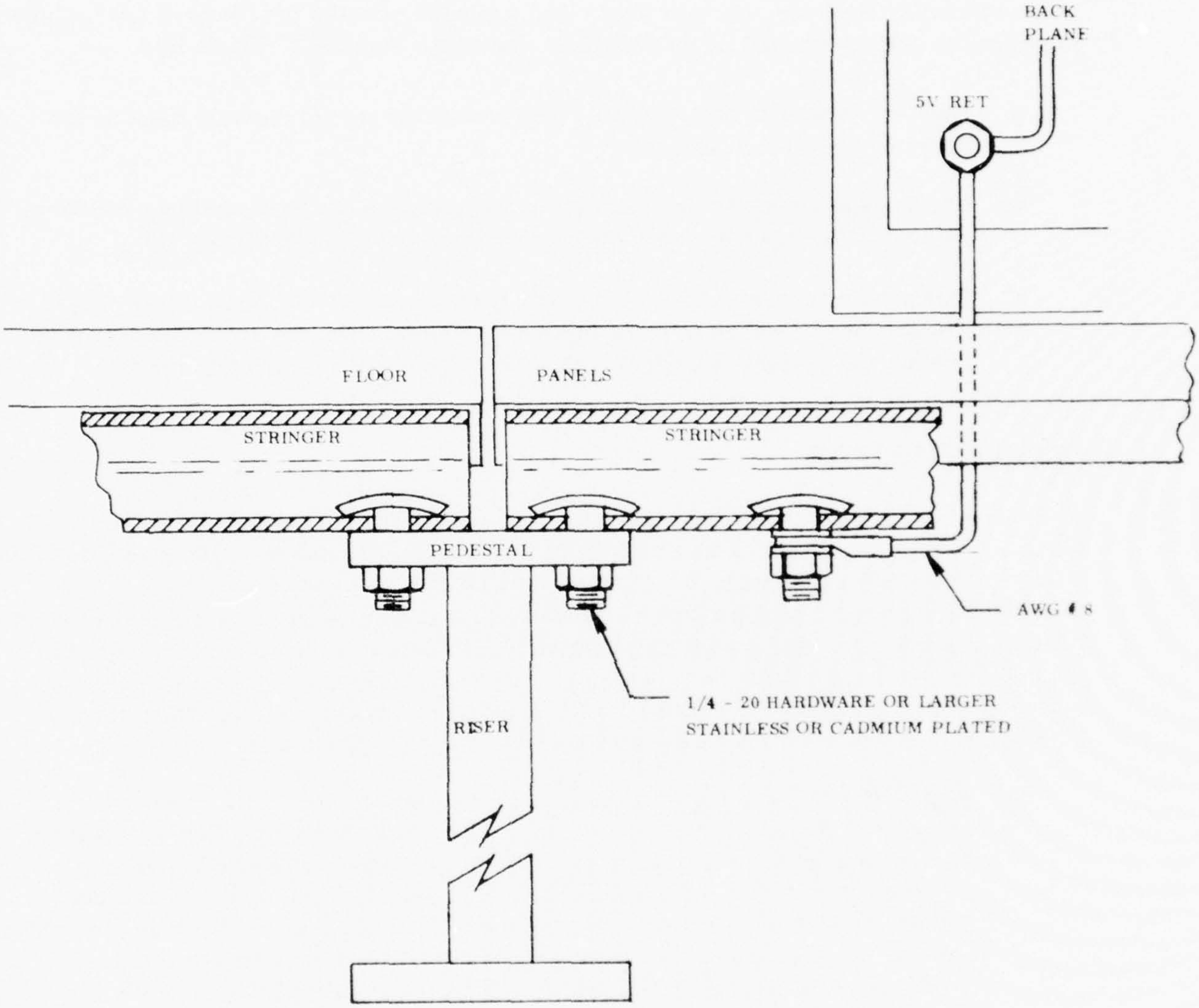

Figure 4. Floor Grounding Detail

(As an example, one of the GE trainers was to be located across the street from a weather radar at Pensacola, Florida. The radar beam has a sidelobe that illuminates the end of the building in which the trainer is located. Field strength measurements were taken at the proposed site of the trainer and compared with the radiated susceptibility threshold of our most sensitive circuits. The trainer intercom used wide bandwidth operational amplifiers which detected the pulse repetition rate of a modulated RF field and caused undesirable interference when tested in the laboratory. The intercom circuit was packaged in a shielded compartment and filtered heavily with considerable improvement. However, the intercabling which was to lie beneath the floor of the trainer at Pensacola was still of concern. A decision was made to install the trainer since we exceeded the RF radiated susceptibility requirement and a fix-if-necessary solution to shield the building's walls had been arranged with the customer. The trainer has been installed for several years now without that problem ever arising. The only difference between our lab test setup and the installation site is that the cabling lies beneath the metallic floor. The floor which was intended to provide for low frequency grounding, 60 Hz to 50 megahertz, also seems to provide a quiet RF cavity between the floor and the earth at frequencies up into the gigahertz range.)

Figure 5 is a photograph of a computer floor during installation at Pensacola. PVC bushings are seen as the conduit interfaces the panel board.

ENCLOSURE TO COMPUTER FLOOR

Individual enclosures and units become referenced to the computer floor's galvanized or aluminum stringers via a jumper cable from the power supply, low side directly to stringer. AWG # 6 or 8 is usually used. The hardware selected to terminate the cable is specified to be compatible, usually stainless or cadmium plated steel.

ENCLOSURE ISOLATION FROM OTHER GROUNDS

It is important that CGI and other components of the trainer system be grounded only through the intended path. If an enclosure must come in contact with a water pipe, building column, or other structure member it must be insulated from that member. This is most common in visual display equipment where a motion platform structure must support CRT display units. An alternative isolation technique that has been used in these types of interfaces is to reference the CRT display to the remote ground directly and isolate the signal ground return path with either a differential line

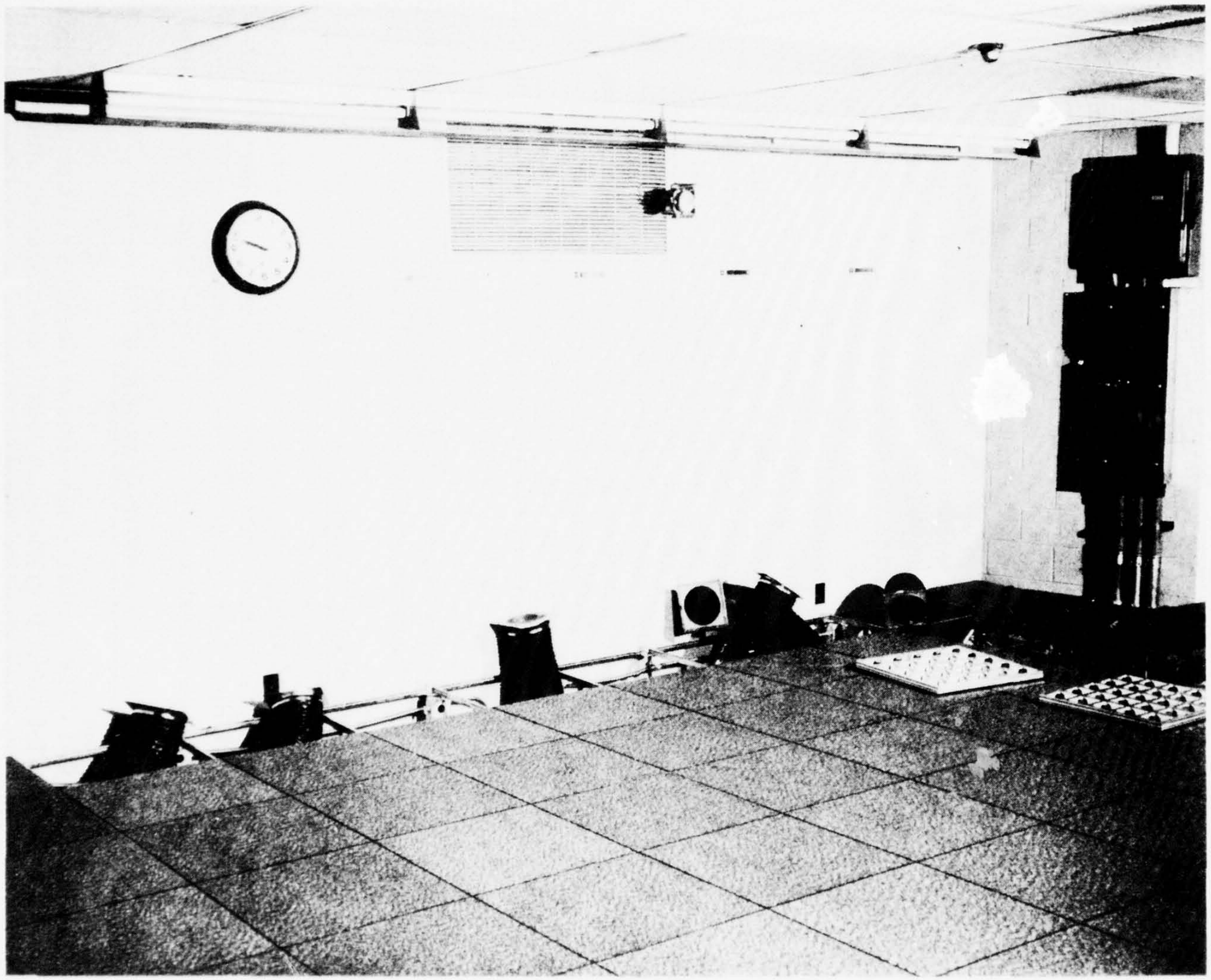

Figure 5. Device 1D23 Floor During Installation

receiver or common mode choke (balun). Both techniques offer satisfactory ground noise isolation. The differential line receiver operates using a virtual ground, usually lying between + 15 volts DC and - 15 volts DC. The device is thus limited in noise rejection to about 15 volts.

The balun is a device which has been used many times by the author to solve ground noise problems. The balun consists of two wires or a piece of coax wound on a ferrite toroidal core. The hot and return are wound together, bifilar, such that signal currents flowing cancel each other's flux, thus zero net inductance is observed to intentional signals. Ground return noise currents are unbalanced, ground wire current exceeds the signal hot current, thus a net flux exists in the core and series inductance attenuates the noise current. Another way to look at the balun is as a transformer where noise in the ground line is transformer coupled to the signal line thus producing the same voltage as the ground system such that the differential voltage is minimized. Figure 6 illustrates several applications of baluns and their effectiveness in reducing ground noise.

LOGIC SIGNAL BACKPLANES

Logic boards containing up to 40 microcircuits each plug into logic card assembly units. Figure 7 illustrates a logic card assembly. Logic blocks are arranged in the logic design such that chip and card locations utilize common ground planes to minimize coupling and to establish an RF transmission path for these 40 megahertz logic rates. The logic assembly backplane plays an important role in minimizing this problem. The backplane design provides a continuous ground plane from card location to any other card location within the logic enclosure.

Signals thus may be transferred from the top of the logic assembly to a bottom location without a direct return wire path. The signal is always propagated on a wire level just over the ground plane such that an RF stripline effect occurs. The flux linkage between signal and ground lies in that controlled air gap path between the wire and the ground plane. Other rules are sometimes added to complex logic assembly backplanes. These may be:

a. Use twisted pair for clock distribution lines over 18 inches in length.

b. Install long runs first, use the Z wire wrap level nearest the backplane (Z_1) for lengths of 18 inches or greater.

NOTE

> Z levels are terms used in wire wrap technology to define the position of the wire wrapped on the pin. Z_1 is nearest the backplane with Z_2 and Z_3 farther from the backplane in descending order. The Z level also identifies the order in which the wire terminations are made.

PROBLEM - Potential differences or "ground noise" between interfacing circuits, subassemblies or racks of equipment cause low level logic to false trigger, analog to be noisy and result in equipment non-compliance with EMI and system noise specs.

DISCUSSION - Ground isolation must be added to sensitive interface circuits to eliminate circulating ground noise currents. This can be done by:

- Physically lifting one end (often impossible)
- Adding differential amplifiers at the receiver end (expensive and common mode limited)
- Adding Baluns or common mode chokes.

WHAT BALUNS DO - The balun forces transmission line currents to be equal and opposite, an inductance effect on non-equal and opposite currents (such as ground currents) breaks up the ground path.

SOLUTION - Baluns or common mode chokes have been used successfully and economically by GE Apollo Systems to break up ground loop in interface circuits. The balun is a lightweight reliable device that can provide 40 db of noise isolation for typical digital circuits.

The device passes d.c. and analog signals without loss or degradation while rejecting transients and spikes of facility and airframe provided ground systems.

Chief advantages:

1. DC coupling is maintained.
2. Droop and transformer recovery problems are eliminated.
3. Cost is small compared to differential amplifiers.
4. Diff amp interface power supplies are not required.
5. Ground noise isolation is good.
6. Signal characteristics are 1 for 1, without delay or attenuation.
7. Components are small and reliable.

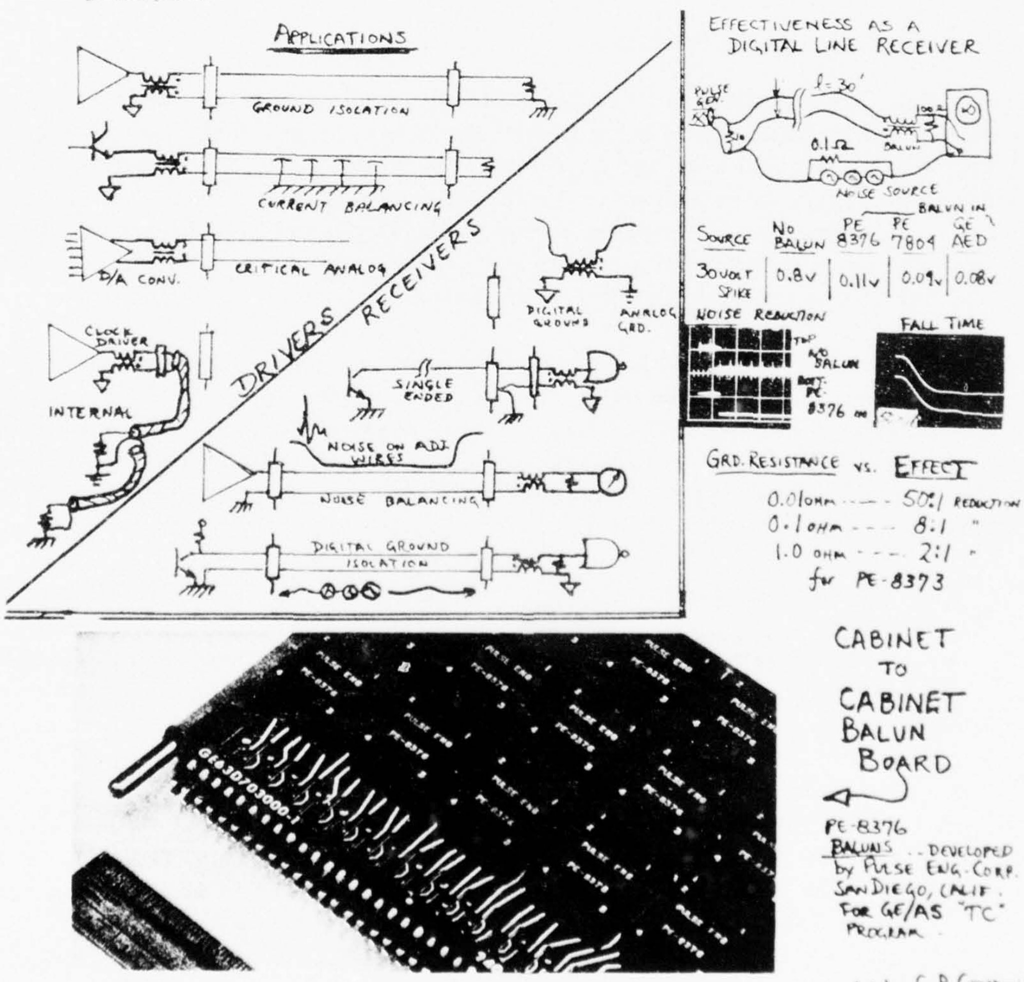

Figure 6. Ground Noise Reduction with Baluns

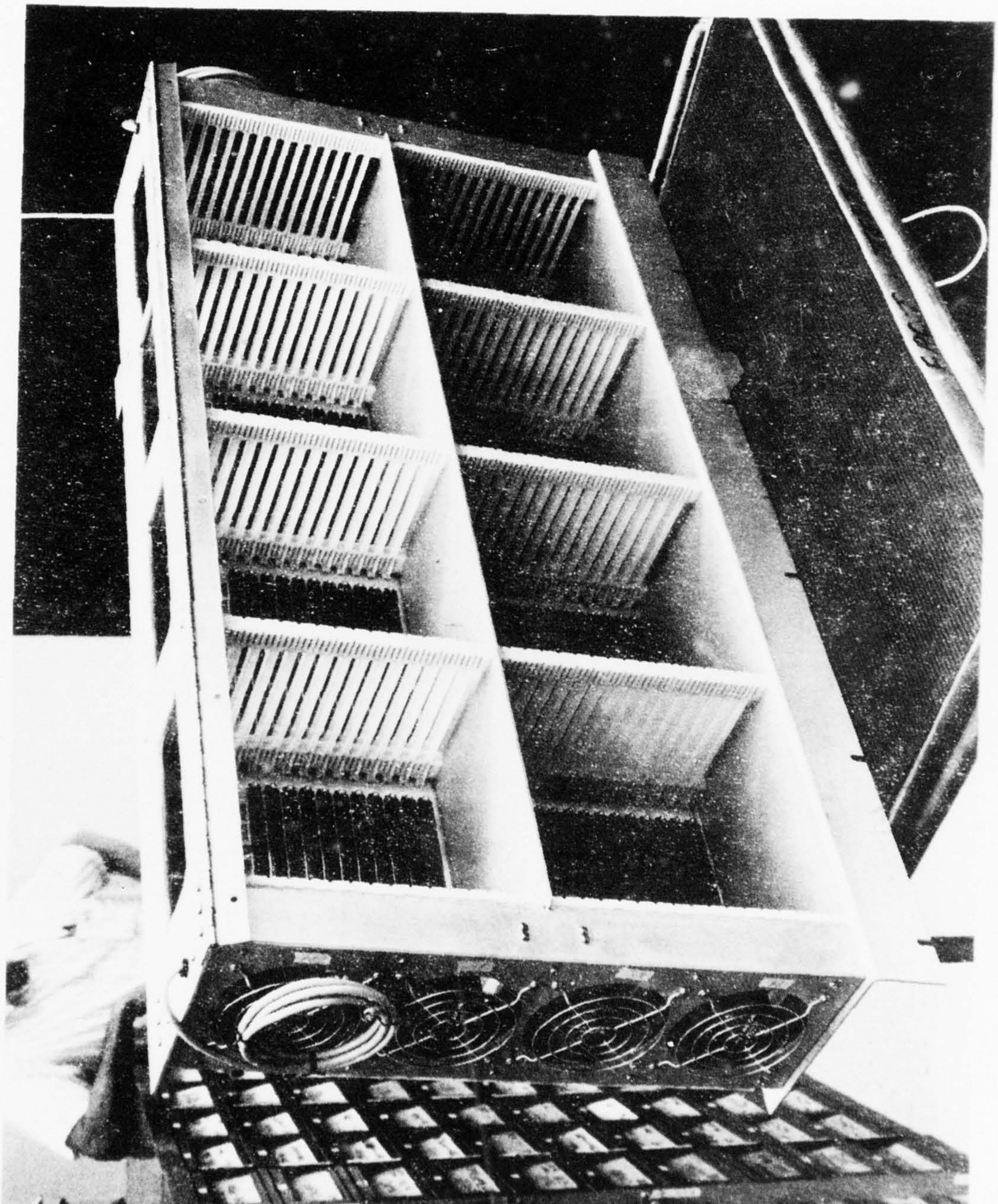

Figure 7. Logic Card Assembly

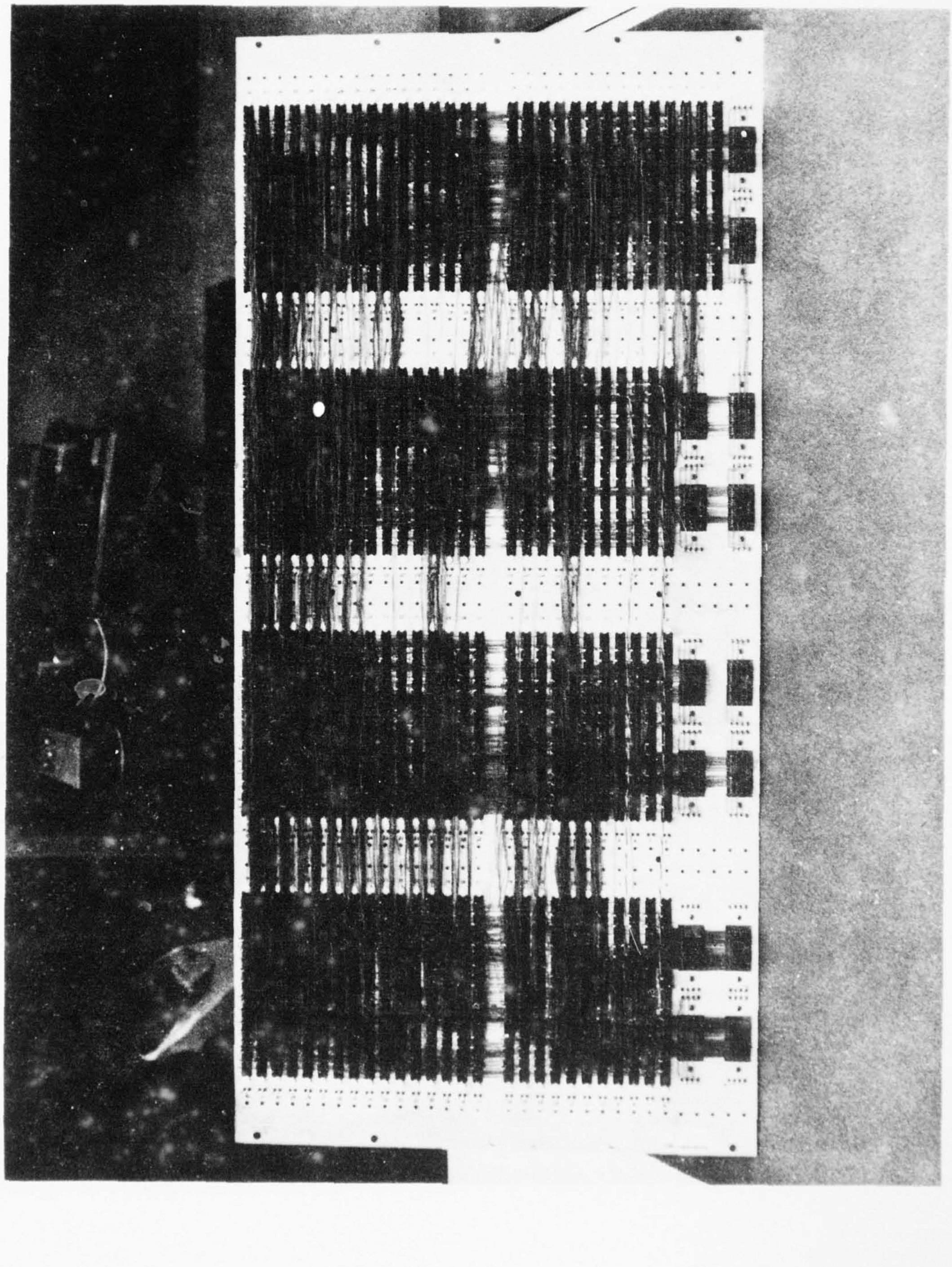

Figure 8. Logic Wirewrap Backplane

c. Add a wirewrap ground grid above the Z_1 level to isolate Z_1 from Z_2 and Z_3 levels. The elevated wire grid acts as an electrostatic shield and as an overhead level ground return system, thus canceling inductive coupling effects. Figure 8 illustrates a photograph of a typical logic wirewrap backplane design used in an Image Generator.

ENCLOSURE TO ENCLOSURE (BACKPLANE TO BACKPLANE)

Numerous signals flow between backplanes of a typical Image Generator. Signal grounds are always carried from backplane to backplane via either a twisted pair or coax transmission line paths. Most recent trainer systems have depended heavily on "shielded wire" for these longer transfer paths. The term "shielded wire" actually refers to miniature coax such as RG-174/U, with the exception that coaxial connectors are not used. The termination of the RG-174/U at connections is handled as with shielded wire. The few inches of coaxial discontinuity through the connection does not appreciably degrade signal waveforms or produce coupling. The advantages are:

a. RFI levels are greatly reduced, coax cancels field radiation.

b. Waveforms are improved, the controlled capacitance allows transitions through the critical one volt threshold region of logic circuits without back porch waveform distortion.

c. Waveforms and coupling are independent of harnessing in the bundle.

d. RG174/U actually costs only 75% of twisted pair and only 42% of twisted shielded pair, per a 1974 GE inventory study.

PRINTED CIRCUIT BOARD GROUNDING

Printed circuit board grounding rules have evolved from standard logic into the switching speeds associated with Schottky logic. Board grounding concepts which worked satisfactorily for standard DTL and T^2L logic have produced problems with the 2-3 nanosecond switching speeds associated with Schottky logic. Two board designs have been developed at General Electric to handle these switching speeds. One is a wirewrap board design for small quantities of a particular circuit, the other is a printed wire board for either large production or critical noise problem boards. Highlights of these grounding rules are:

PRINTED WIRE BOARD

a. I/O Pins - 12 ground pins equally spaced along the connector are used to permit I/O signals to be routed adjacent/nearby ground.

b. Dedicated Board Ground Runs - The 12 ground pins are connected to ground runs (0.050 inch wide) and run up the board as equally spaced as is possible. These may be moved somewhat or staggered to relieve congestion, however this practice is as minimal as possible.

c. The board design is then done as normal. Microcircuit grounds are tied to the board's horizontal ground runs as continuous as possible. Vertical jumpers 0.010 inch wide are added to tie the ground runs together. These are added at each row where space is available.

d. The board is then re-examined and a landfill technique used to fill in the open areas with ground plane. Planes/sections will exist on both sides of the board and they are interconnected with plated-through holes on their edges/corners wherever possible.

e. When complete the board should have the following characteristics:

   (1) When held to the light the board is almost opaque due to copper.
   (2) Microcircuits are referenced together vertically as well as horizontally.

WIREWRAP BOARDS

The basic wirewrap board design for CGI and other training devices incorporates a ground plane on one side of the board with the 5 vdc power plane on the other side of the board. The basic board has some unique grounding features to foolproof the logic board design process from an EMI standpoint. These are:

a. 12 evenly spaced I/O pins are dedicated to grounding the board's ground plane. This alleviates problems where designors or draftsmen try to reduce or just neglect grounding.

b. Wirewrap rules have been programmed into the wirewrap computer program to minimize wire to wire coupling. The program and automated wirewrap system produces:

   (1) Wire length analysis, maximizes Z_1 layer lengths, minimizes Z_2 lengths.

   (2) Adds a wirewrap ground grid. Programmed in ground wires added in each row and column to separate Z_1 from Z_2 wiring.

   (3) Adds hold down jumper wires to maintain minimum elevation of wiring to the ground plane.

These rules have been successfully applied in several trainers. A test example case indicated coupling on the typical board had been reduced by 64%. Typically, wire to wire coupling on the board can be kept below 0.5 volt by using the ground plane and these simple wirewrap rules. Figure 9 illustrates the low noise wirewrap board developed for high speed logic.

CONCLUSIONS

Grounding and ground noise is an environmental condition that is often ignored or left to an EMC specialist to resolve. This is not only true in trainers but aircraft, ships and spacecraft. I maintain that this condition still exists in 1977 because the

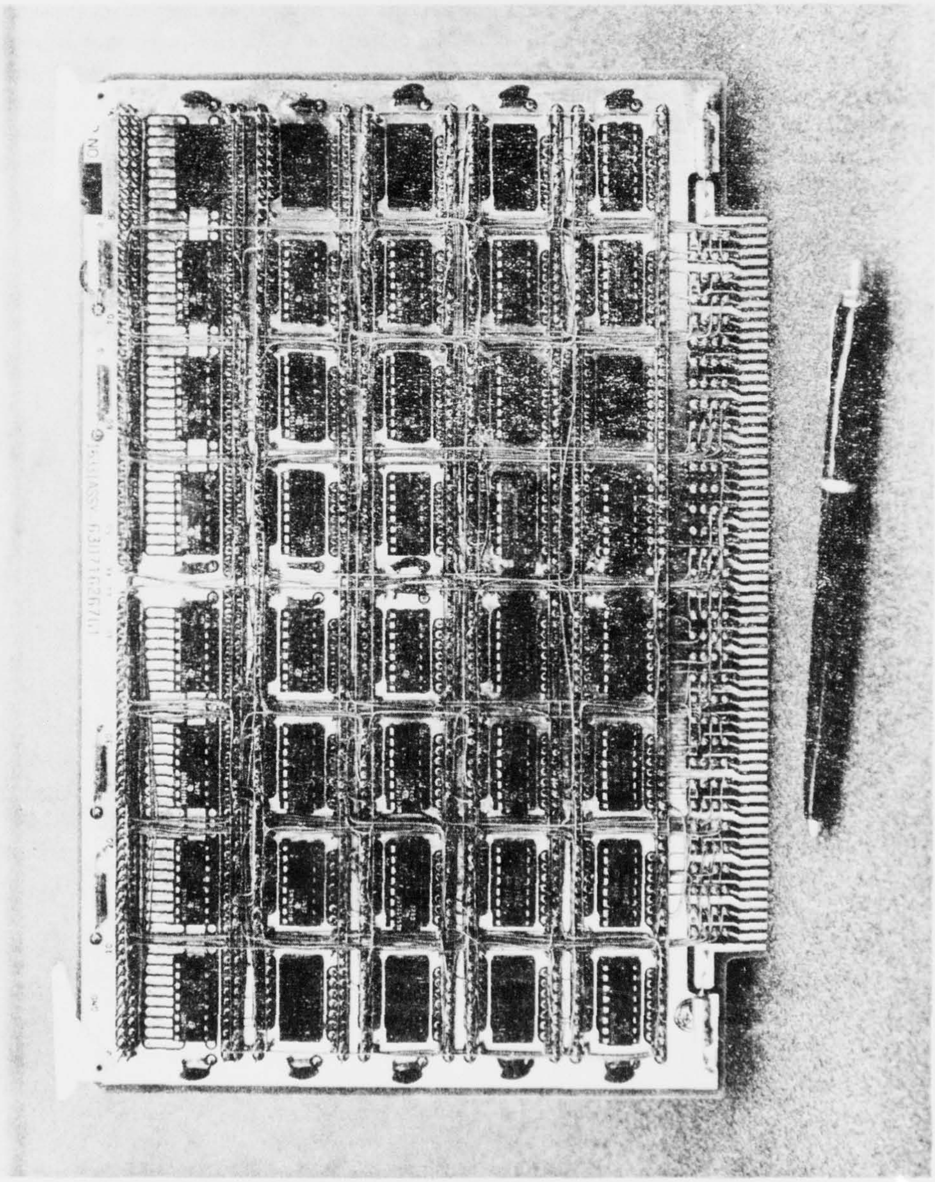

Figure 9. Logic Wirewrap Board

EMC community does not specify ground noise quantitatively. General Electric is attempting to make this transition on the DSCS III satellite where a multipoint grounding concept is mandatory due to the nuclear threat and space plasma charging and discharging conditions. For this application, General Electric specifies that components limit their unbalanced power line current, thus the noise injected into the ground system is minimized. The specifications also require that interfacing components be tested by injecting ground noise currents (spikes) between their chassis grounds. This requirement drives current interface designers to consider common mode noise as well as the standard normal mode noise. Hopefully, more engineers will realize that the real EMC problems occurring are caused by grounding negligence and thus will take corrective action.

ON THE DESIGN OF CHASSIS GROUND NETWORKS USED IN LARGE SCALE DIGITAL SIMULATOR SYSTEMS

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

A network of conductors must be installed in large scale digital simulators and trainers to form a chassis ground reference in the overall grounding system. The network is used to maintain equipment chassis at equal potential for safety reasons and is also used as the reference ground for high frequency equipment. In recent years, simulators and trainers have increased in size and the electrical and electronic equipments have had to process higher and higher frequencies. Consequently, the importance of the chassis ground network has become more prominent. For these reasons, the design and implementation of chassis ground networks has become a subject of special interest to personnel responsible for grounding systems.

This paper describes the components and installation methods that have been successfully used to form practical low impedance chassis ground networks in several large trainer and simulator systems. This paper describes network configurations, types of conductors used, and bonding methods employed. The measured resistance values of several networks are presented.

On The Design of Chassis Ground Networks Used in Large Scale Digital Simulator Systems

G. W. Gowdeski
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Abstract

A network of conductors must be installed in large scale digital simulators and trainers to form a chassis ground reference in the overall grounding system. In recent years simulators and trainers have increased in size and the electrical and electronic equipments have had to process higher and higher frequencies. Consequently, the importance of the chassis ground network has become more prominent. For these reasons the design and implementation of chassis ground networks has become a subject of special interest to personnel responsible for grounding systems.

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Introduction

The chassis of the various electrical and electronic equipments in large scale digital simulators and trainers must be interconnected and grounded to the building electrical safety ground through a network of conductors. The network serves two purposes in the overall grounding scheme. It is used to maintain equipment chassis at equal potential for safety reasons and it is also used as the reference ground for high frequency signal returns and cable shields. Because of the frequencies involved, a low impedance network is essential for effective performance and care must be exercised in the selection and configuration of components. For these reasons the chassis ground network deserves special attention.

Although many noteworthy articles have been written about grounding systems, discussions related to the design and implementation of chassis ground networks have been notably absent from most publications.

Therefore, it would seem logical and timely to describe existing systems so that, after review and criticism, recommendations for improvement can be proposed.

This paper describes the components and installation methods that have been successfully used to form practical low impedance chassis ground networks in several large trainers and simulator systems.

But, before proceeding to the chassis ground network it may be beneficial to describe the overall grounding system.

Overall Grounding System

The grounding system in a trainer or simulator facility is comprised of separate ground references for primary power returns, signal circuits, and equipment chassis. Power and signal circuits are equipped with wired returns. This grounding method implements the single-point principle at low frequencies and multiple-point principle at high frequencies. The advantages of this hybrid grounding approach have been described by other authors[1].

There are two reasons for the separate ground references. One reason is to isolate primary power current from chassis ground to ensure safety. Another reason is to prevent interaction and coupling between power and signal circuits that would otherwise result in unwanted conducted interference.

Customarily, high frequency signal returns are terminated to chassis ground using the multiple-point grounding principle, while low frequency signal returns and primary power returns are isolated from chassis and are separately and independently returned to the building electrical safety ground point. Although the chassis ground network does not normally conduct low frequency signals or primary power current, it must be designed to have this capability to prevent a build up of dangerous voltage levels in event of an electrical short. In either case a low impedance network is essential. Resistance is another important consideration, because contracts often specify that DC resistance between any two cabinets must be less than 5 milliohms when measured between the cabinet chassis ground points. The impedance of a large network of conductors is complex and difficult to evaluate. On the other hand DC resistance measurements are relatively easy to perform and give a good indication of the effectiveness of bonded connections. For these reasons care must be exercised in the selection of components and in the configuration of the chassis ground network.

Component Section and Network Configuration

When selecting the components to form the chassis ground network some of the more important considerations are inductance, resistance, current carrying capability, size, availability, and cost. Although wires and solid conductors can be used, copper tubing is a reasonable compromise among these considerations and is often used to form the main conductors. Ground straps must be used to connect equipment cabinets to the tubing.

Figure 1 shows the floor plan of an existing simulator with copper tubing arranged in radial configuration. The heavy lines represent three lengths of 3/4 inch continuous Type K copper tubing that are approximately 15, 32, and 34 feet long. Continuous tubing, available in reels, was used to avoid the need for soldered joints. Ground straps of shortest practical length were used to connect the tubing to the equipment cabinets and to the system ground plate to minimize inductance and resistance. Of course, the system ground plate, shown as the filter panel, was similarly connected to the building ground point.

Flat, flexible, tin plated copper ground straps were used to make the various connections. Flat straps present a lower impedance than wires; flexible straps resolve the mechanical problems of creepage and expansion; tin plating helps to prevent corrosion when joining dissimilar metals. Ground strap dimensions vary with application. Width is normally 2 to 3 inches, while length may be 9 to 18 inches. Current carrying capability is dependent on circuit breaker rating. Most power distribution systems use many circuit breakers rated at 15 and 30 amperes. Ground straps are normally designed to conduct on overload current of 5 to 10 times circuit breaker rating or about 100 to 300 amperes.

In large installations where a great number of conductors must be used in grid configuration to lower the network inductance and resistance, the use of copper tubing has practical limitations.

In a large facility, an elevated floor system of rigid grid construction is normally installed and the grids or stringers are used as the main conductors of the chassis ground network. The ground straps used need not differ from those used with copper tubing. Figure 2 shows components of a rigid grid floor system. The floor stringers are bolted to the pedestals to form a grid of two-foot squares. Rigid grid floor systems are available in steel or aluminum and are designed to have low resistance characteristics. Figure 3 shows the floor plan of an existing trainer that contains an aluminum rigid grid floor system. An aluminum floor was used because measurements showed its resistance was much lower than that of a similar steel floor.

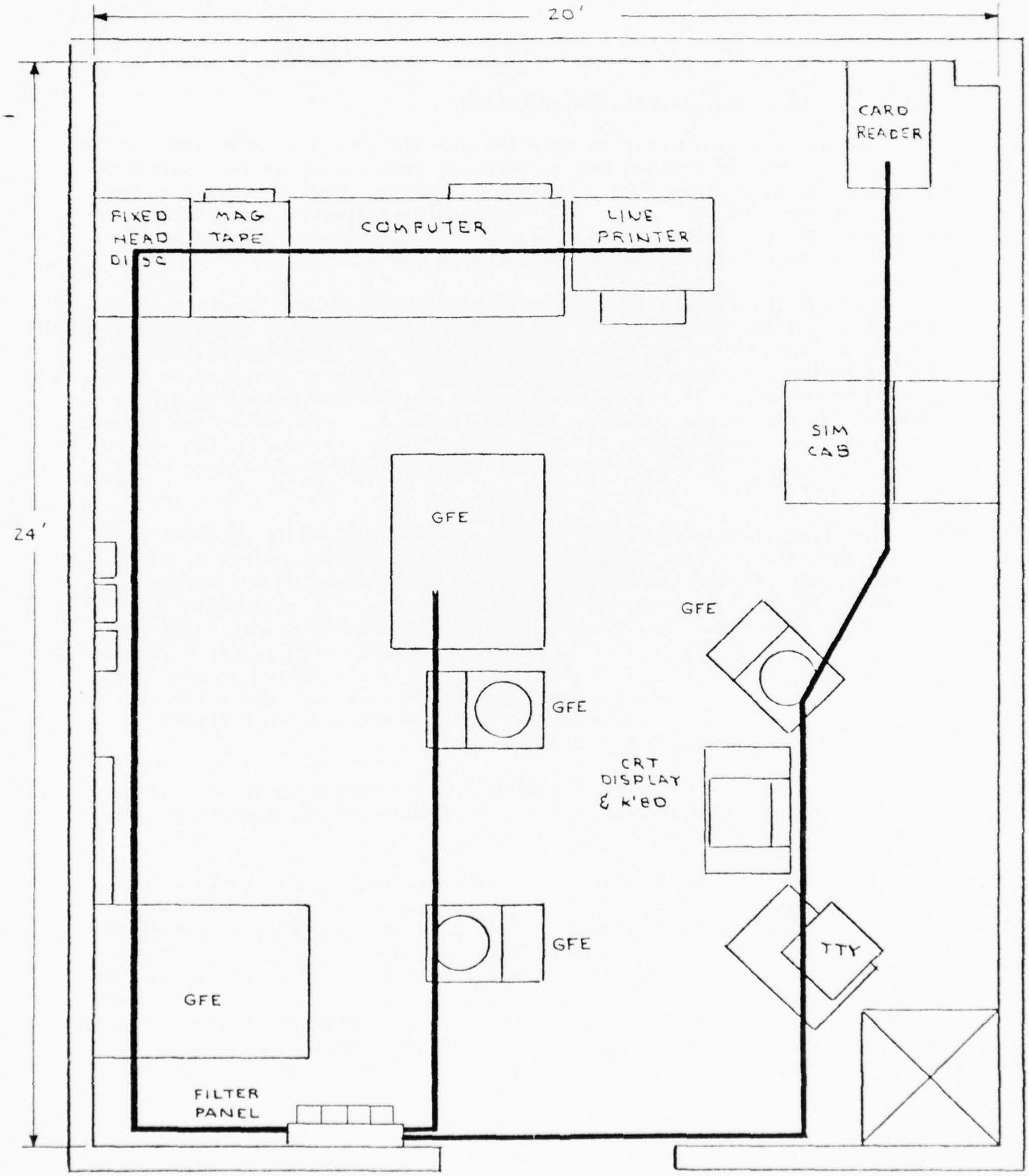


Figure 1. Simulator Floor Plan

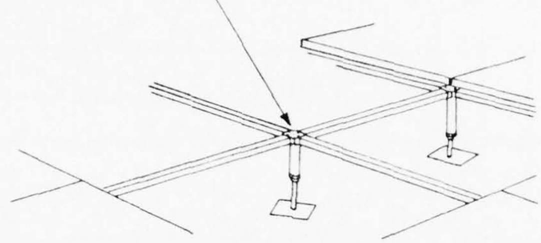


Figure 2. Rigid Grid Floor System

Bonding Method

When installing ground straps the bonding method must ensure a long lasting low resistance connection. Although welded connections are often preferred, bolted connections are adequate for most applications, are easier to install, and also enable quick alteration should the need arise.

In the systems that have been described the bolted connection methods shown in Figure 4 were used with a conductive sealing compound and were found to be adequate for this application.

Network Resistance

Referring again to Figure 1, the heavy lines shown represent three separate lengths of 3/4 inch continuous Type K copper tubing that are approximately 15, 32, and 34 feet long. The DC resistance of this type of tubing is approximately 51 microhms per foot. Measurements have shown that the average ground strap resistance and the contact resistance of bolted connections is slightly lower.

Resistance measurement were made from the system ground plate to each equipment cabinet. The measured resistance levels ranged from about 1.5 to 5.0 milliohms, with no measurement exceeding 5 milliohms.

For the trainer shown in Figure 3, resistance measurements were made from Unit 17 to all other cabinets. The results of the measurements are shown in Table 1. All resistance levels were less than 5 milliohms.

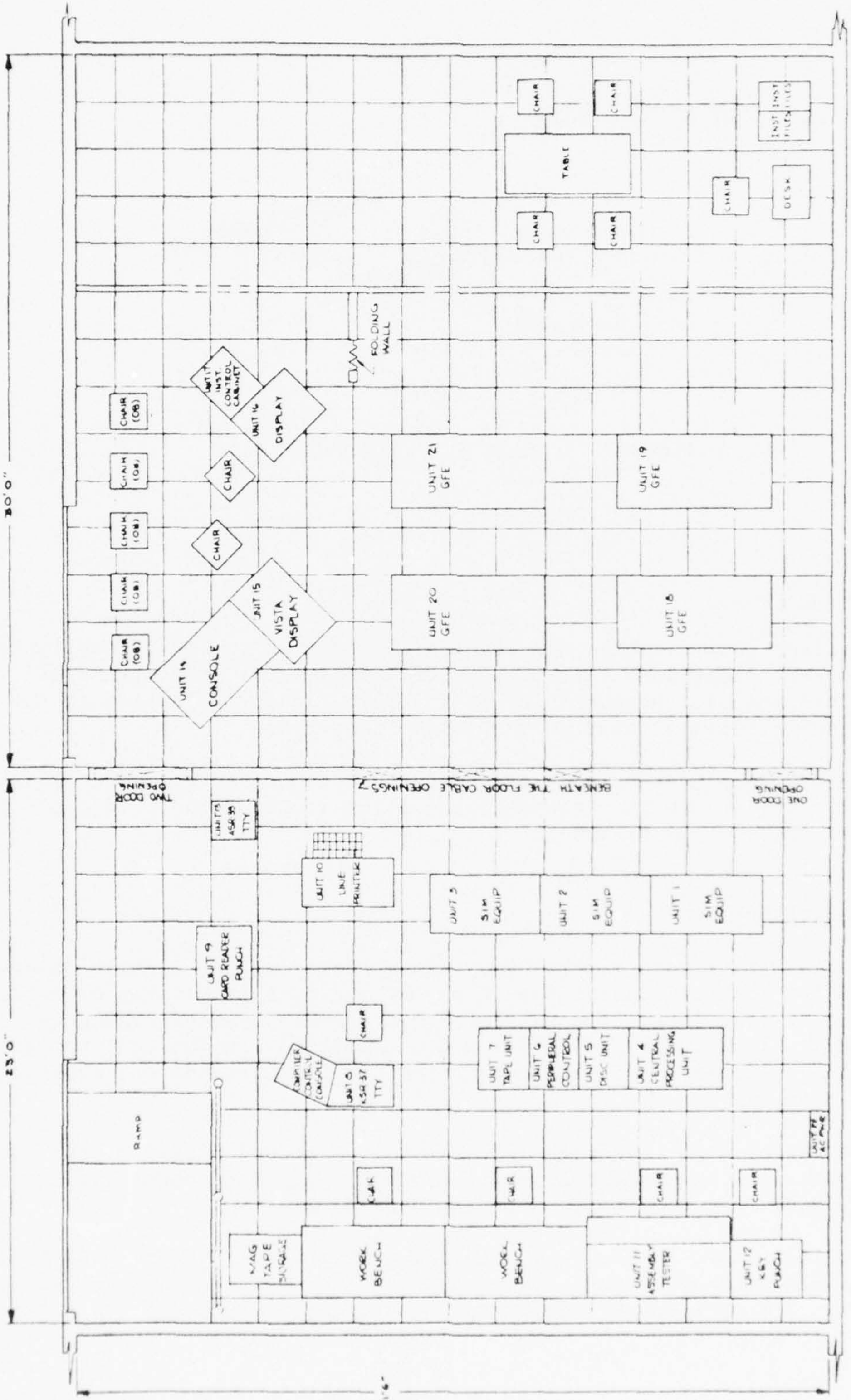
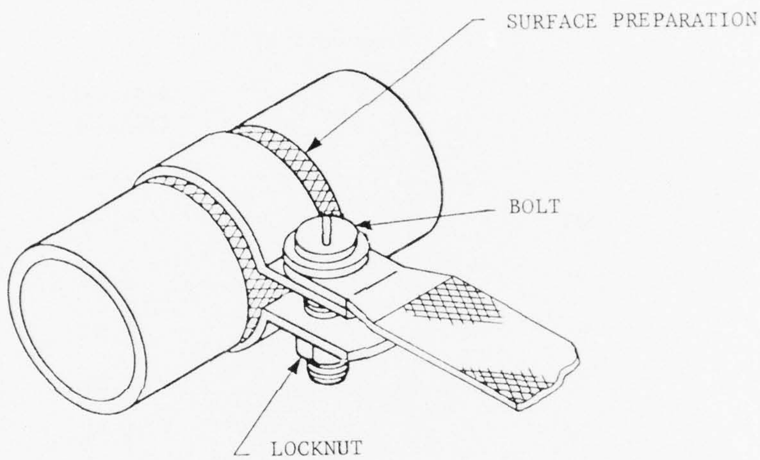
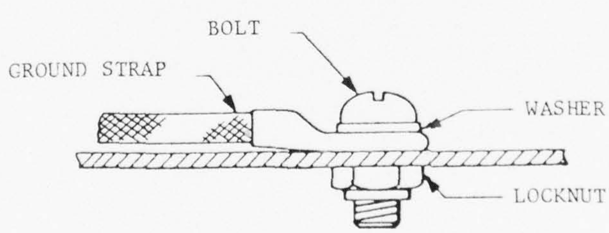


Figure 3. Trainer Floor Plan



a) CLAMP CONNECTION - GROUND STRAP TO TUBE.



b) CONNECTION - GROUND STRAP TO CABINETS & POWER PANELS.

Figure 4. Bolted Bonding Connection Methods

Table 1

From Unit 17 to:

UNIT	RESISTANCE (MILLIOHMS)
15	2.34
16	1.79
14	2.26
18	1.53
19	1.31
20	1.29
21	1.22
1	2.40
2	2.97
3	2.65
4	3.60
10	3.55
7	3.55
6	3.40
8	3.51
9	3.83

Conclusions

From the limited applications that have been described, we may conclude the performance of the chassis ground network is dependent to a major de on the components used and on the network configuration.

It has been shown that:

1. Copper tubing arranged in radial configuration is adequate for small installations.

2. False floor systems arranged in grid configuration is a close approximation of an ideal reference ground and can be used in large installations.

3. Bolted bonding methods were adequate for ground strap connections in the installations described.

Digital simulators and trainers will continue to increase in size and us equipment that must process higher and higher frequencies. Therefore, a of the design considerations discussed herein should be continually eval so that recommendations for improvements can be proposed.

Reference

H. W. Denny and J. A. Woody, "Considerations In The Design of a Groundir System for A Complex Electronic Facility", 1974 IEEE Electromagnetic Compatibility Symposium Record.

DESIGN GUIDE FOR THE UTILIZATION OF RAISED (COMPUTER) FLOOR SYSTEMS AS AN INTEGRAL PART OF THE GROUNDING SYSTEM

by

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Presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

ABSTRACT

Raised floors are commonly used for elevating electronic cabinets above the sub-floor allowing cables, ducting and piping to be routed out of view. Bolted-Grid floors can also be used for providing an effective ground reference. This paper discusses and gives design guidance on the selection, testing and installation of raised floors for grounding purposes.

Maximum scale factor values derived from an analagous floor model are presented for floor sizes of 38' x 58', 58' x 58', and a family of 28' wide floors ranging in length from 18' to 118'. The scale factor allows the user to determine maximum worst case point-to-point resistance for a floor based on grid resistance, pedestal to grid junction resistance and straight line point-to-point distance.

INTRODUCTION

Electrical noise problems have reduced the efficiency of electronic training systems such as flight, weapon and war game simulators. A number of these problems have been associated with simulator grounding system design. Most large scale simulators utilize a combination of operational, commercial and contractor-designed equipments and subsystems whose signal ground systems are seemingly incompatible. It was hypothesized that grounding problems due to poor bonds, common and long grounding conductors would be avoided if an equi-potential ground reference system could be provided. Since most simulators were provided with a raised floor system it was felt that if a low resistance could be achieved between the metallic parts of the floor structure that this vast network would provide an equi-potential reference system.

The information contained in this paper represents their use for several years. Included in this discussion are:

a. Background information on raised floors

b. Raised floor specifications

c. Experiences and problem areas

d. Raised floor model

BACKGROUND INFORMATION ON RAISED FLOORS

Raised Floor Systems.

Raised floors are used to structurally support equipment cabinets and provide a space between the original facility floor and raised floor plates for cabling, air plenum or air conditioning ducting, piping, drains, etc. Raised floors provide an esthetic room appearance. Three general types of floor systems manufactured are: a) the free-standing, stringerless or pedestal-only type; b) the drop-in grid or removable grid type; and c) the bolted-grid (stringer) or rigid grid system.

Free-Standing, Pedestal Only or Stringerless System.

The pedestal only system is shown in figure 1. The pedestal base is glued or "shot" in place to form the basic understructure. The pedestal heads are leveled and floor panel installed. The conductivity between distant pedestals is variable and unreliable, making it unsuitable for a ground reference.

Drop-in or Removable Grid System.

The Drop-In Grid System is shown in figure 2. The grids or stringers are retained by engaging pins or depressions in the pedestal head. The stringers supply support and when newly installed provide comparatively low resistance contact to the pedestal head. Equipment cabinets resting on the floor panels provide increased contact pressure in certain areas. Severe corrosion and unreliable electrical contact have resulted due to dirt, moisture and floor cleaning/waxing compounds filtering through

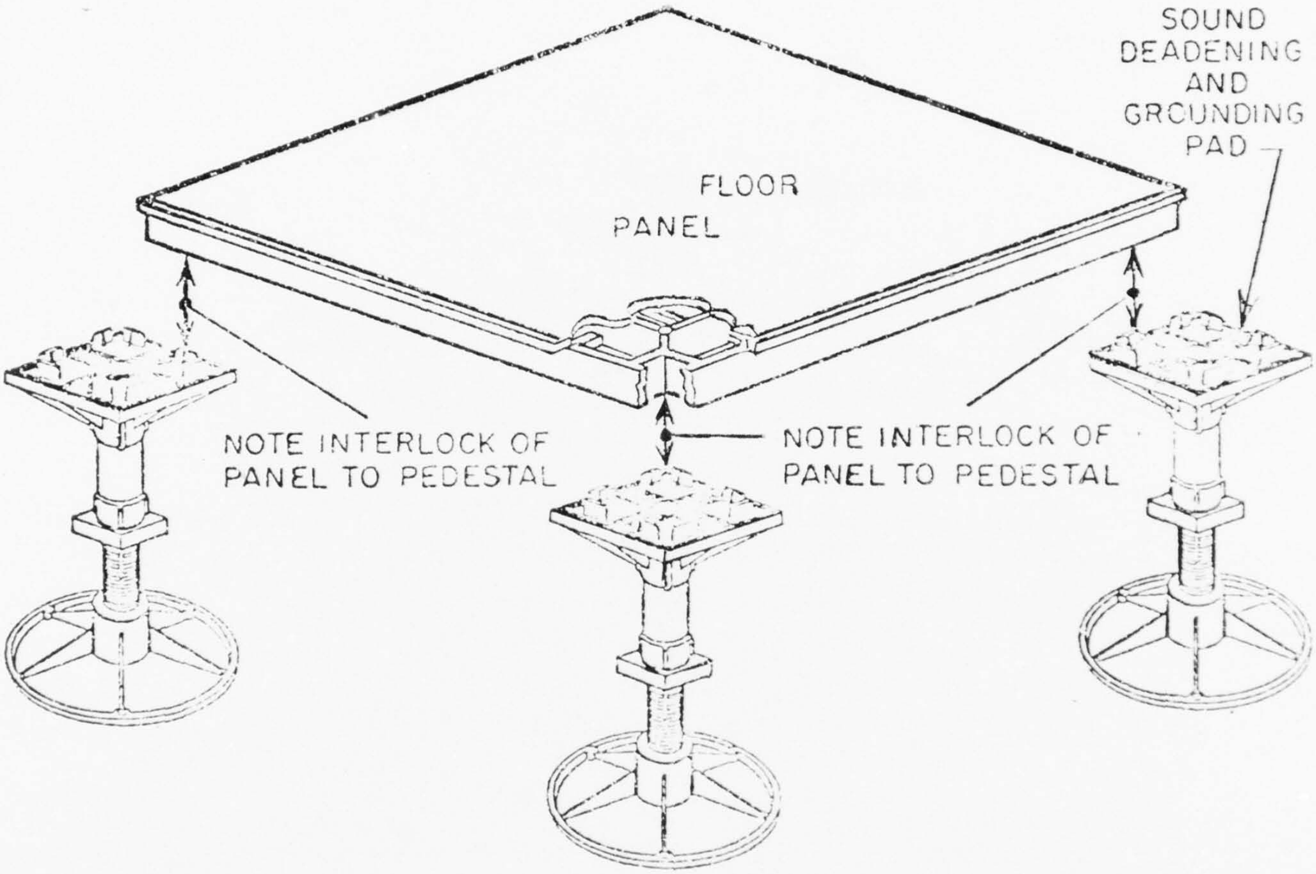


Figure 1

Example of Pedestal Only

Floor Construction

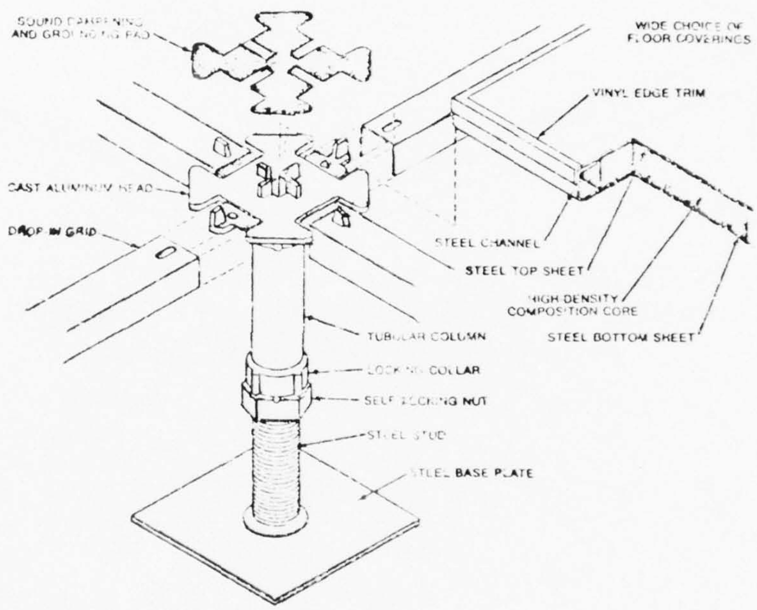


Figure 2

Example of Drop-In Grid

Floor Construction

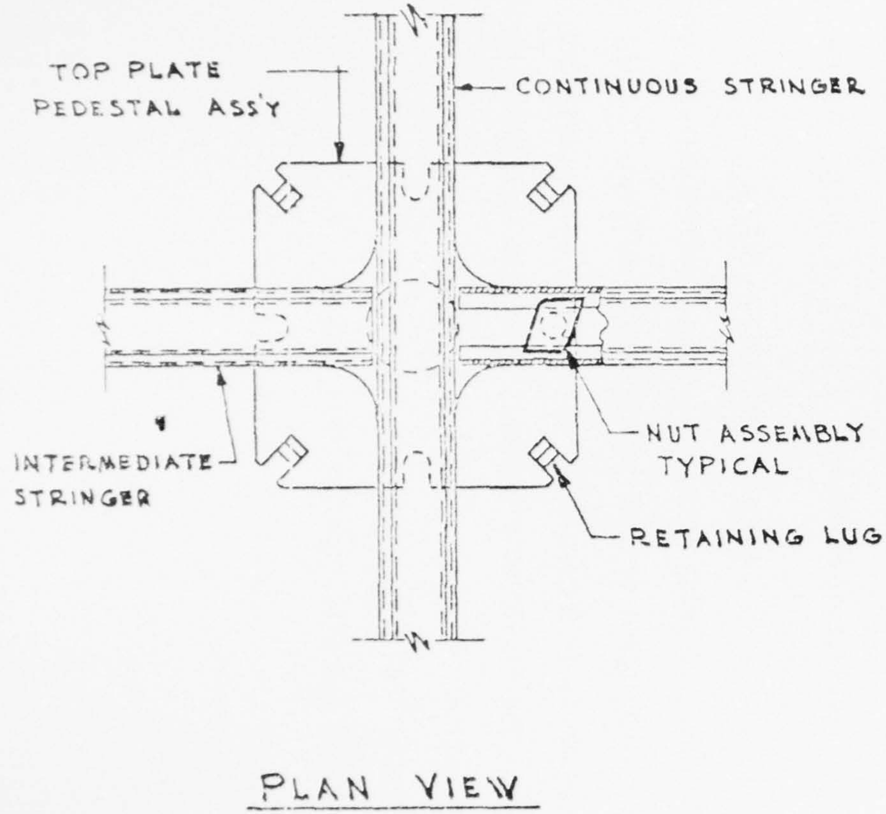
crevices. This floor system is also considered unsuitable for a reference plane. Floor panels resting on the pedestals and grids are commonly 24" x 24" although they may be purchased in 30" x 30" dimension.

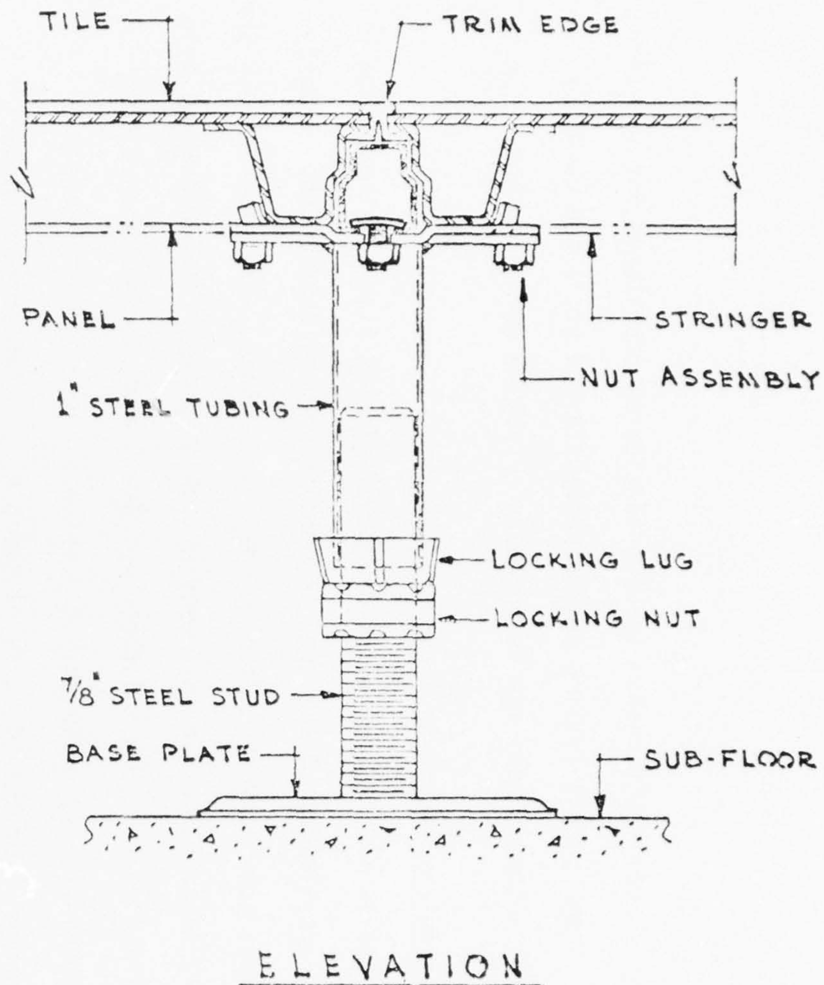
Bolted-Grid (Stringer) or Rigid Grid System.

Shown in figures 3, 4 and 5 are bolted-grid floor systems. The systems are similar to the drop in grid except the grids, when properly installed, are securely bolted or clamped in place. The floor panels are normally 24" x 24" as in the removable grid system. The individual grid lengths may vary. Some manufacturers use "main" stringers that span three pedestals (approximately 6') while the "cross" stringers are less than 2" (for the 24" x 24" floor panel). Materials used for stringers and pedestal heads are steel and aluminum. Standard floor panels are steel or aluminum with a selected floor covering.

RAISED FLOOR SPECIFICATIONS

The Naval Training Equipment Center (NAVTRAEQUIPCEN) wrote and issued a raised floor specification (MIL-F-29046 (TD)) in 1974 which is included with amendments in Appendix A. As problems are experienced, amendments are made. The first two amendments have been because of problems requiring resolution. This document is actively used in raised floor procurement by NAVTRAEQUIPCEN. It is unknown whether other government agencies have raised floor specifications at this date.





Rigid Grid Floor System Details
Figure 3

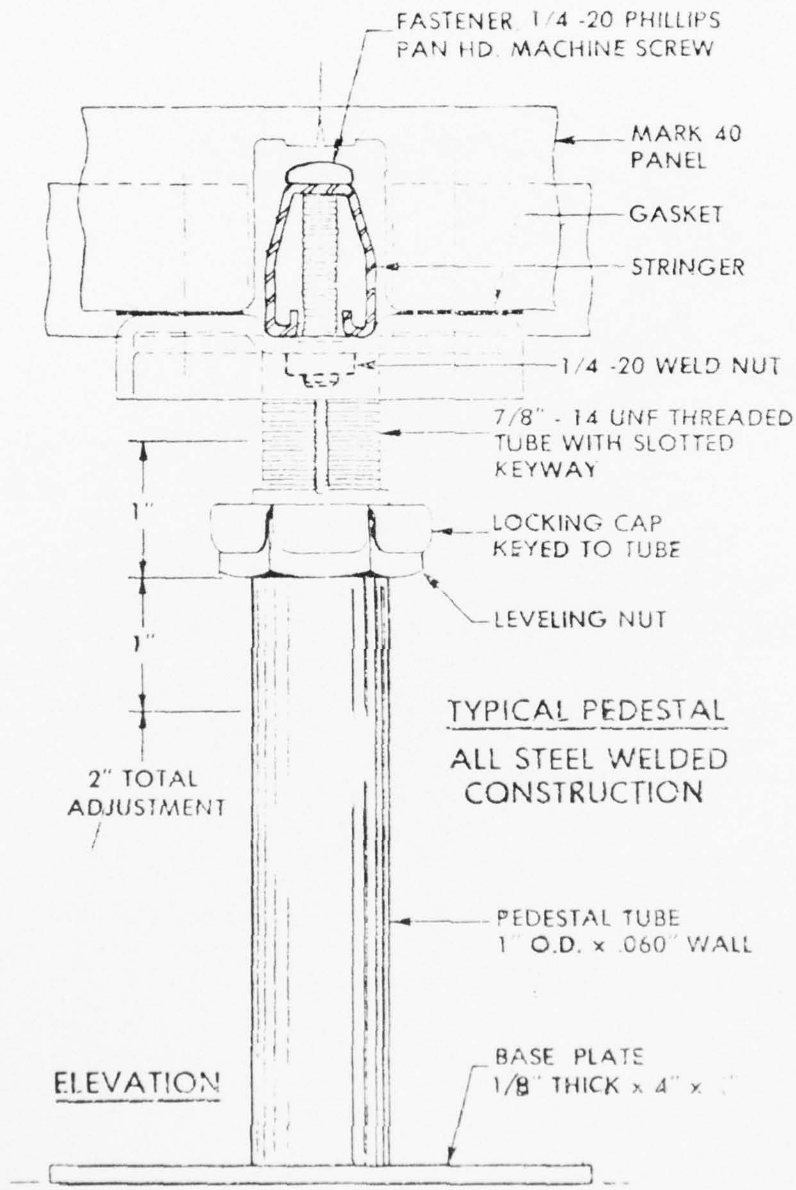


Figure 4

Example of Rigid-Grid

to Pedestal Bolted Connection

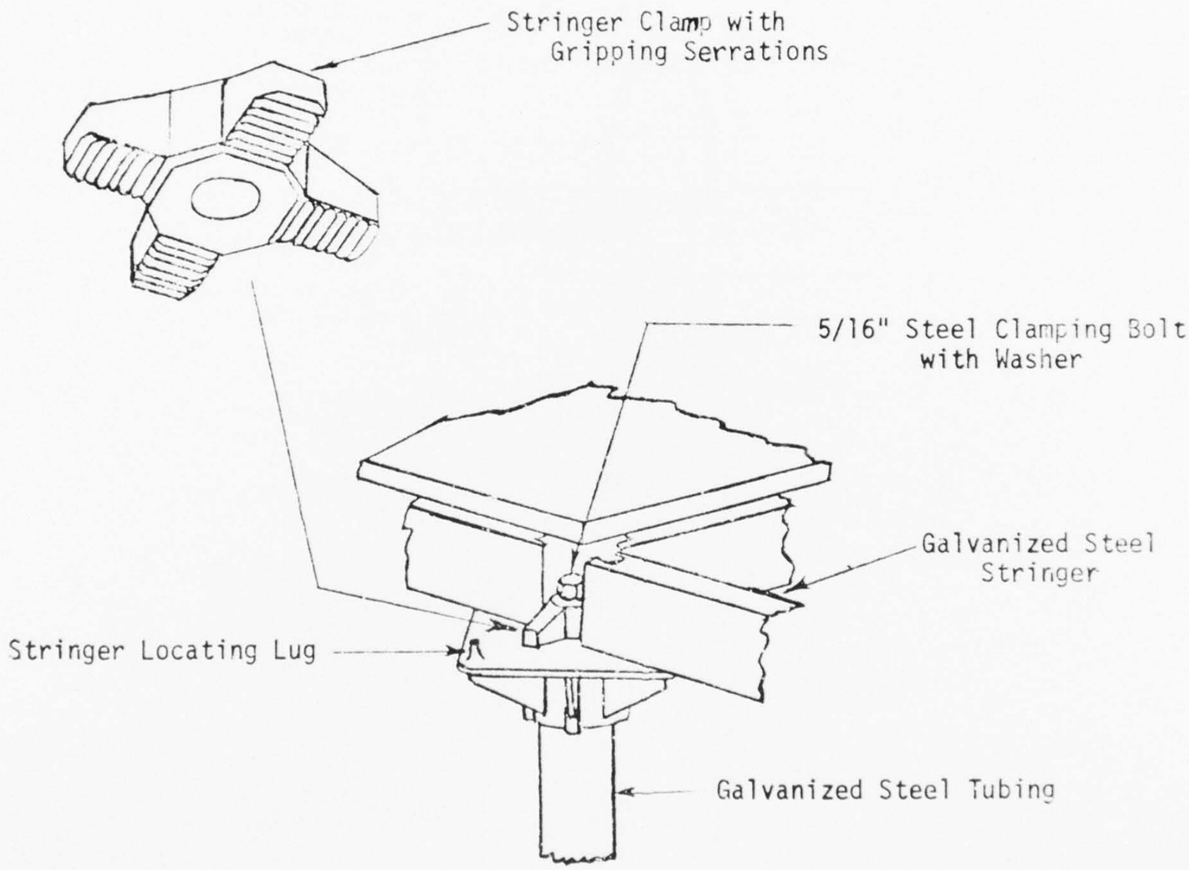


Figure 5

Example of Rigid-Grid

to Pedestal Clamped Connection

EXPERIENCES AND PROBLEM AREAS

The experiences, in general, in using raised floors for a ground reference have been excellent. Problem areas that designers should be aware of are:

a) Installation practices

b) Site preparation

c) Floor system checkout

Installation Practices.

Installation practices have caused poor bonded joints between pedestal heads and stringers. These are primarily due to:

a) Pedestal heads heavily oxidized and dirty when bolted

b) Use of poor bolting hardware
(speed nuts, sheet metal screws)

c) Bolting hardware not installed or not properly tightened

The installation contractor may receive aluminum pedestal heads from the manufacturing plant that are heavily oxidized. The joint surface requires minor abrasion and perhaps a light coating of a joint protective compound. The joint compound should be particularly considered for non-carpeted floors where moisture, cleaning compounds and wax would settle, degrading the joint (sometimes severely) in a several year period.

The use of improper bolting hardware has caused unreliable joints. In one case the floor manufacturer used sheet metal screws to hold the stringer to the pedestal. Another floor system that previously used standard nuts changed the design to use a "clip" nut which deformed, stripped fastener threads and created loose joints. This "clip" nut

is shown in figure 6 and is called the grid lock nut by the manufacturer. MIL-F-29046 was modified to specifically prohibit the use of that type of hardware.

It is recommended that the installation crew be briefed and the floor tested, if possible, with floor panels not installed.

Site Preparation.

The basic problem of installation site preparation is the avoidance of undesired metal contacts from facility ducting, piping and structure. These inadvertent contacts present a definite problem in checking out the floor installation. It is mystifying to read decreasing resistances as distance between reference and test points are increased.

The raised floors that were first used for reference ground networks were isolated from the facility. A number of later installations were compromised severely through multiple contact to other metallic structures. No interference problems have been experienced at these sites. It is unknown whether leakage currents from the facility were injected into the ground reference system or, if so, the raised floor structure presented such a low impedance that potential approaching the interfering level were never reached, perhaps both.

Floor System Checkout.

Raised floor systems that were provided with the simulator were not tested separately. The contractor was required to not to exceed a specified resistance value, usually 5 milliohms, between cabinet chassis. The policy of the government supplying the floor at the training facility has led to

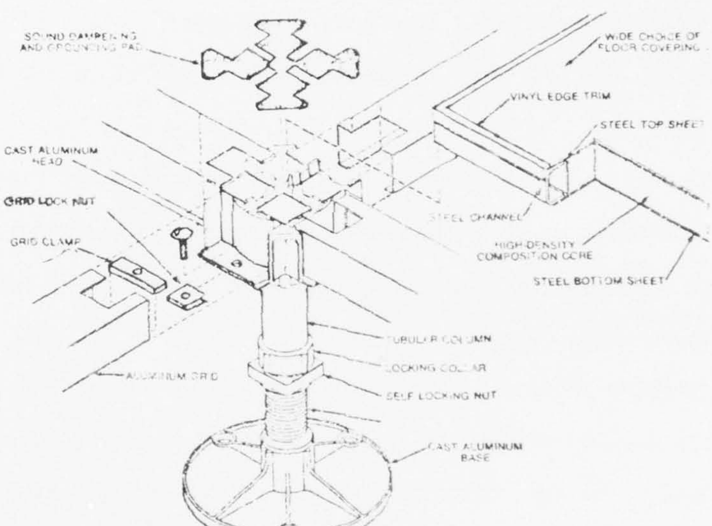


Figure 6

Example of Unacceptable Grid

to Pedestal Bonding

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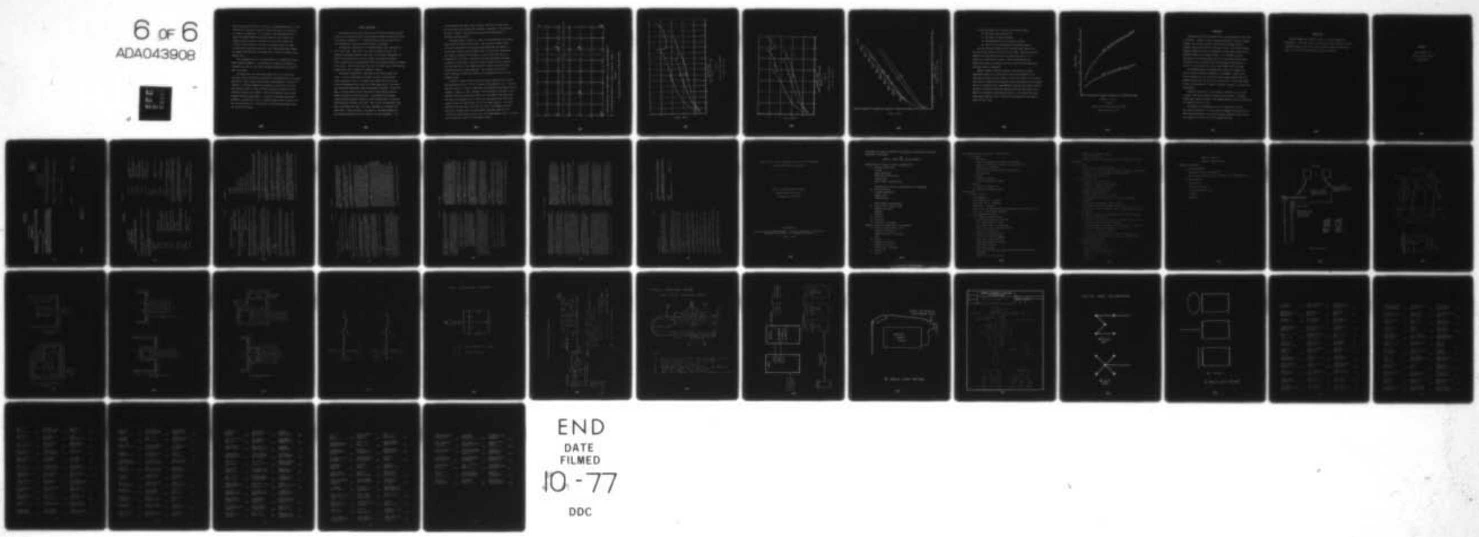

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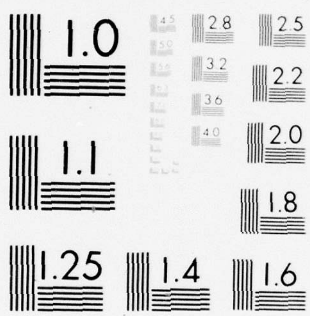


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

need of ensuring the floor is suitable as a ground reference over a long term period. The specific means of testing the floor as a system has not been fully determined. To this point, tests have been limited to making resistance measurements between pedestals and stringers and between arbitrary points of the floor grid (with floor panels and training system) installed. Typically, a pedestal head to stringer resistance will read about 40 μ ohms. The specification (MIL-F-29046) was changed from 500 μohms to 100 μohms as an effort to eliminate poorly bonded joints.

The instrument used for field measurements is a modified Shallcross Model 670A Milliohmmeter. The instrument was changed from battery to AC power input and test leads were lengthened enabling 75 foot measurements to be made.

A problem arose with field measurements when poor installation practices coupled with multiple connections to building metallic structures were found. The resistance readings were unpredictable as a function of distance. To further compound the problem was the specific resistance value between points of large, isolated, properly installed floors of arbitrary dimensions was unknown. Poor joint connections were located through individual measurements. To solve the resistance measurement problem on a system basis led to a computer program search (unsuccessful) and the construction of a scaled model of the floor grid without panels for typical floor sizes.

RAISED FLOOR MODEL

An analagous raised floor model was constructed to determine expected worst case resistances between pedestal heads of floor sizes typically used in simulator installations. A definite problem exists with the floor or its installation if the calculated resistance is exceeded.

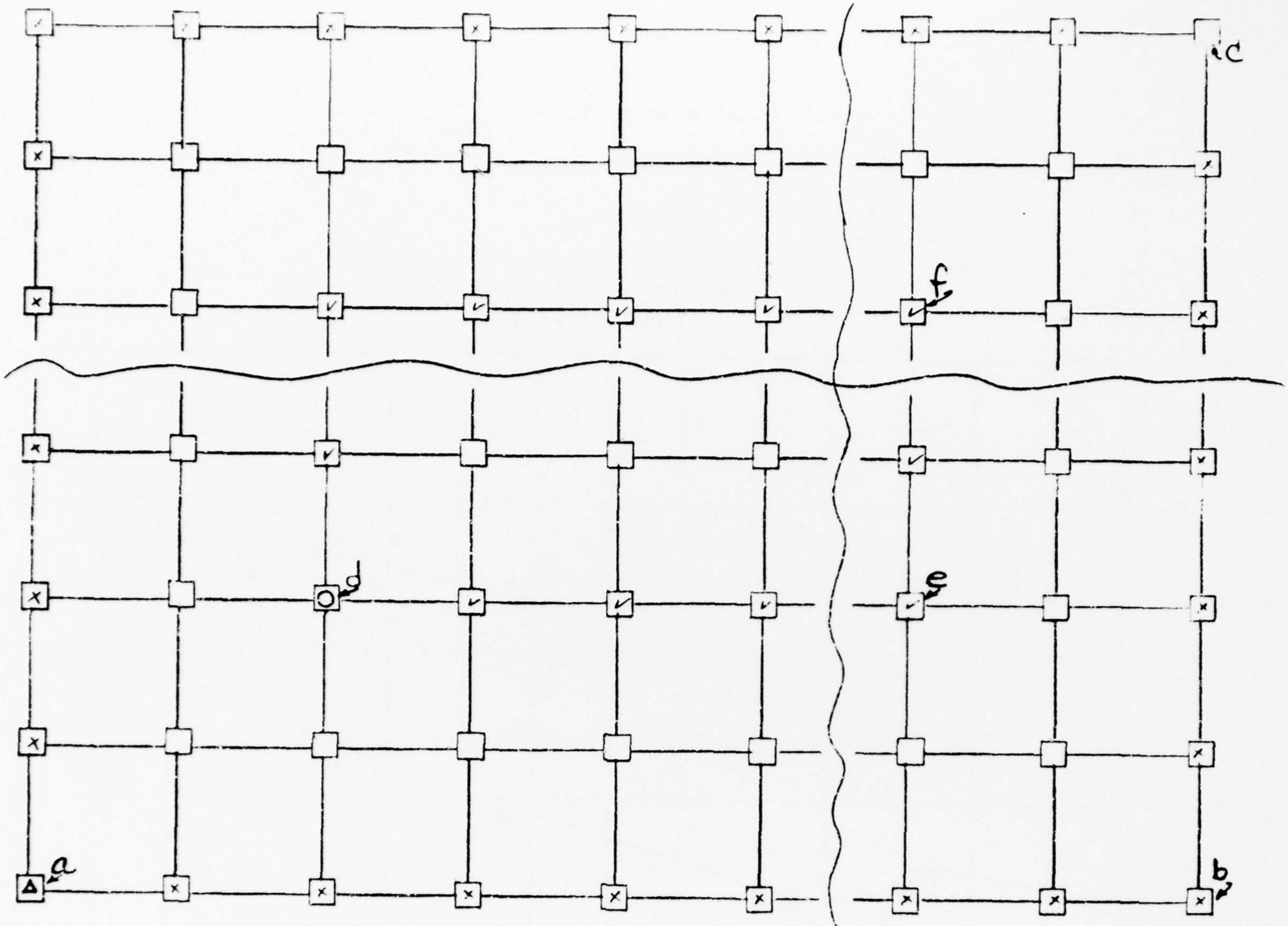
The model was constructed of 12 terminal boards, each representing an 8' x 28' floor. Over 1700 1 KΩ $\pm$ 5% resistors were used. The terminals represented pedestal heads while the resistors represented the total of the grid and the two grid to pedestal junction resistances. The 1 KΩ resistors are approximately 10^6 times the actual values encountered in the field. Due to high usage of the 24" x 24" floor panels the resultant graphs reflect the 2' pedestal to pedestal distance.

Three sets of measurements were made on the various model floor sizes. The first represented the highest possible resistance that could be obtained. That is, an edge corner pedestal was used as one point and measurements were made to all other edge points. The second set represented measurements made from pedestals located 4' in from the edge. This was selected due to the actual minimum spacing required between electronic cabinets and walls. Considering that the bond straps from the equipment cabinets are desired short, the 4' in spacing simulated actual hardware conditions. The last set of measurements were made to determine the lowest resistance obtainable in a straight line measurement. These were made in the center of the model beginning at the center and working towards the edge in two foot increments. This

value represents the lowest value resistance that one can expect when the floor panels are excluded and no multiple connections to the building are made. Figure 7 illustrates the measurement philosophy that is related to the data graphs.

The graphs shown in figures 8, 9 and 10 are the designer's resistance value guides for selected floor sizes. The scale factor shown on the axis was calculated from the measured value between the two pedestals at the model distances shown divided by the 1 KΩ resistor representing the single grid and joint resistances. Figure 8 gives the data on a simulated 58' x 58' floor. The peak on the top curve (edge) represents an increase of the corner to corner resistance (points a to b, figure 7). The final end point is the diagonal (point c, figure 7) with the lower intermediate points at edge pedestals. The distances after the 58' point represents straight line distance to the pedestals from the corner reference point.

On the 4' in graph (figure 8) the first peak represents the distance and resistance to the 4' in to 4' in corner points (points d to e - figure 7). The final point (f - figure 7) represents the distance and resistance to the diagonal. Figure 9 is done similarly. The first peak of the graph is the maximum value at the indicated distance (the 38' corner in the edge case). The values of the edge and 4' in curves are the maximum values calculated. Figure 10 takes in a whole family of 28' wide floor sections. Each peak represents the edge corner to corner resistance. The diagonal shown by the dips in figures 8 and 9 has been deleted from this graph since it is equal to or less than the main curve. The slight peaks in the 4' in curves were deleted due to their increase being so minor.



△ EDGE MEASUREMENTS FROM CORNER PEDESTAL (REFERENCE) TO ALL EDGE PEDESTALS (MARKED x)

○ 4'IN MEASUREMENTS FROM REFERENCE TO ALL PEDESTALS 4'IN FROM EDGE. (MARKED ✓)

Figure 7

Illustration of Model Test Point & Measurement Method

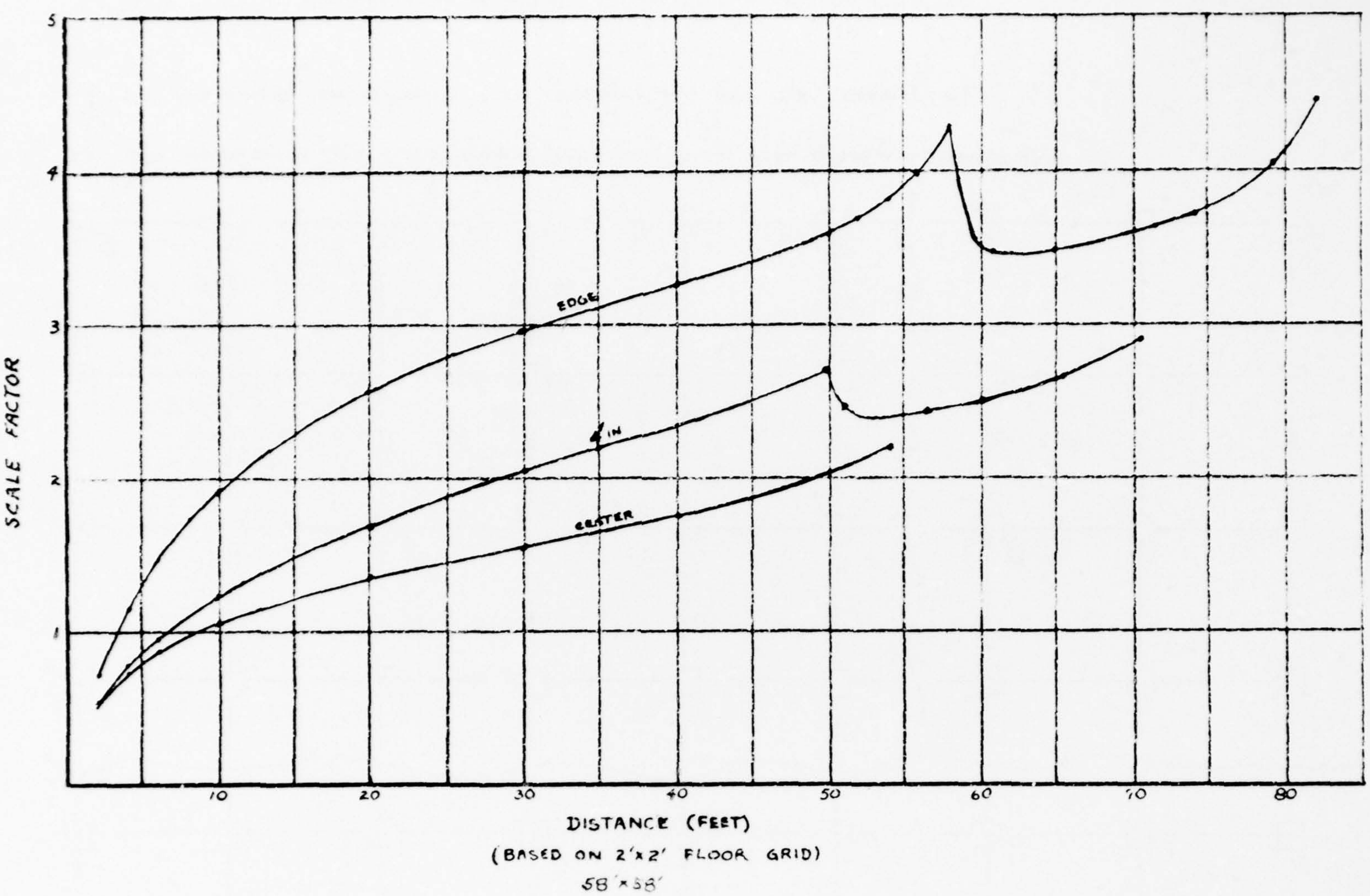


Figure 8

Scale Factor Determination

for 58' x 58' Floor

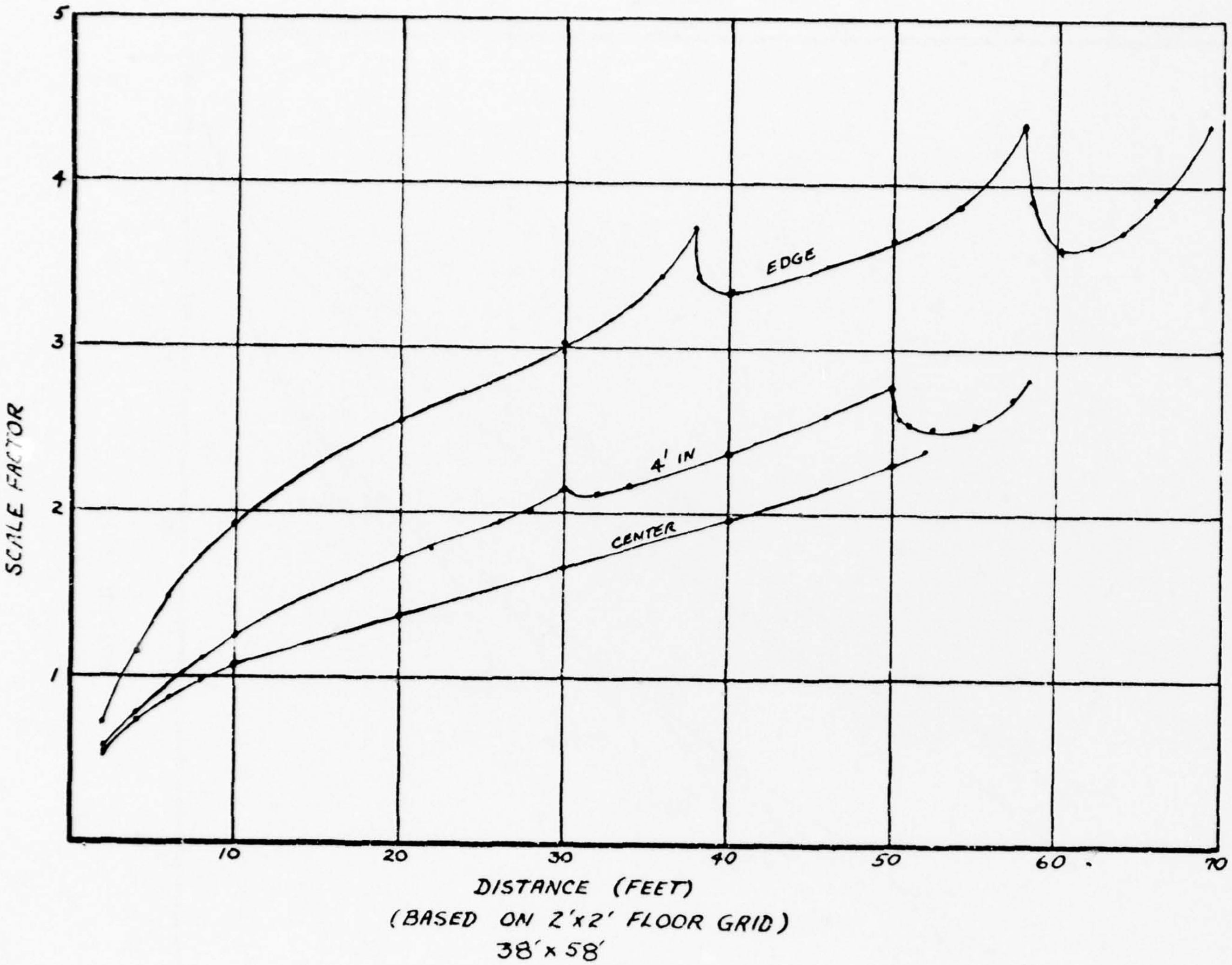


Figure 9

Scale Factor Determination

for 38' x 58' Floor

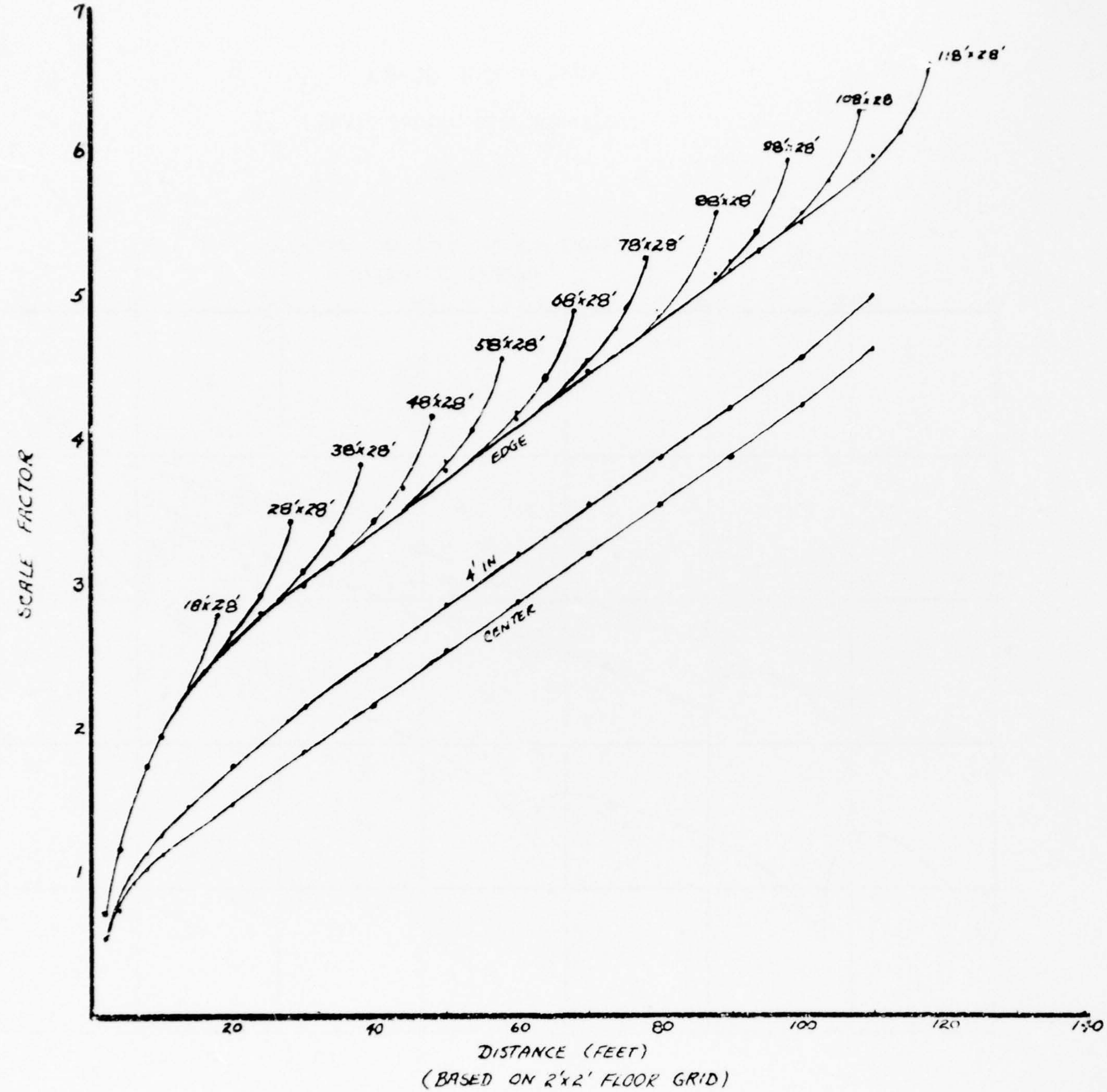


Figure 10
Scale Factor Determination for a Family of 28' Wide Floors

To use these graphs the following items should be known:

a) The floor external dimensions

b) The actual stringer resistance

c) The maximum permissible junction resistance

d) The at line distance between floor points desired

The floor external dimensions will determine which graph to use. Use the one with closest dimensions if not listed. Select the distance between points desired and rise to the appropriate edge, 4' in or center line. Read the scale factor. Add the stringer and two junction resistances, multiply by the scale factor and the theoretical resistance value is determined.

Figure 11 shows a comparison between calculations and actual measurements made on an isolated floor using steel stringers of the type shown in figure 3 with a typical junction resistance of 30 μ ohms and floor panels installed and making good contact with pedestals and stringers. The use of conductive vinyl sound deadening pads and grid strips increases the value to the point where the lowering of the resistance due to the panels is considered a non-controlled gratuity. Even those floor panels with copper grounding "clips" cannot be relied upon due to the fragile nature of the "clips".

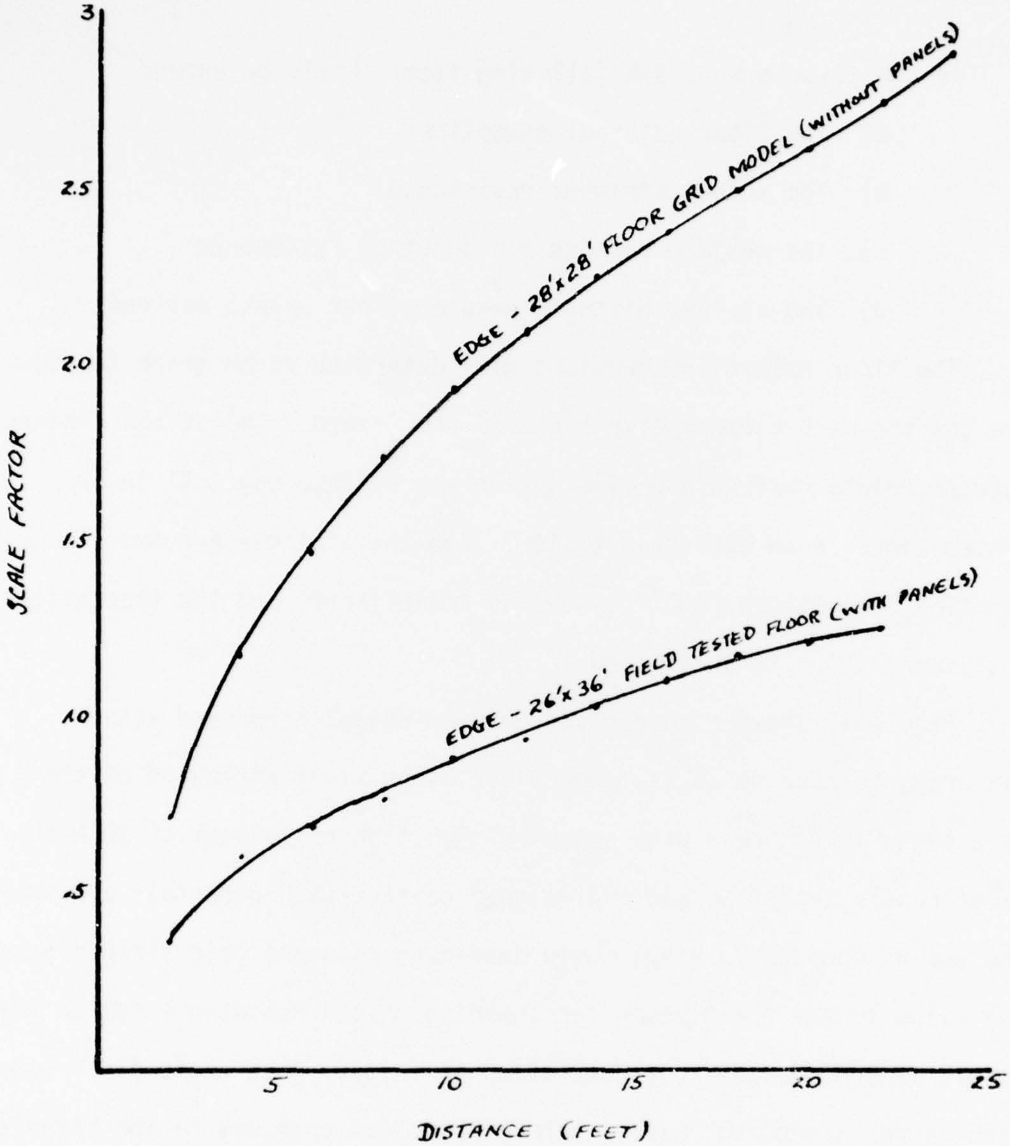


Figure 11

Scale Factor Comparison between Model and Field Tested Floor

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Connections from the electronic system and outside world to the floor is important. Clamps, if used, should be installed on the upper pedestal assembly to avoid the relatively high resistance between the lower assembly (that has the base) and the upper column. The grid to pedestal fastener hardware can often be changed to allow bolting a bonding cable terminal directly to the pedestal head. It is feasible to obtain additional grid locking hardware and use it to bolt the bonding cable terminal to a grid. Another means of terminating a bonding cable is to drill a hole and bolt it to a non-heavy weight bearing stringer.

In extremely humid environments where corrosion is common, the use of corrosion prevention compounds is recommended. Bolted joints can be covered with a non-corrosive silicone-rubber compound that will protect the joint for the life of the installation. An ice cube rubbed on the silicone-rubber will smooth it and make it appear as a professional installation.

Carpeting selected as a floor-covering, should be of a low static or static free type to prevent possible spurious signals or component failure when touching hardware. MIL-F-29046 contains this but surveillance is required to ensure its use.

To determine the degradation, if any, of the floor with time, resistance measurements and method should be documented and available so that repeat measurements can be made if ground reference system problems are suspected or periodic checks for degradation made.

CONCLUSIONS

The MIL-F-29046 specification provides a base for raised floor procurements. Utilizing it plus the guidelines in this paper will provide a ground reference system that is well-designed, properly installed and lasts for the life of the electronic system installation.

APPENDIX A

MIL-F-29046 (TD)

Flooring, Raised, General

Specification

MIL-F-29046(TD)
Amendment - 1
30 September 1975

MILITARY SPECIFICATION

FLOORING RAISED;
GENERAL SPECIFICATION FOR

This amendment forms a part of Military Specification MIL-F-29046(TD), 1 November 1974 and has been approved by the Naval Training Equipment Center, Department of the Navy.

Page 10

Add the following new paragraph.

"3.7.1 Grounding - Grounding and grounding systems shall be in accordance with MIL-T-23991. The connection from two earth ground rods shall be made by a cable clamped to two elevated floor pedestal head assemblies that are at least 4 feet apart. The resistance between the pedestal head assembly and the cable shall be less than 0.5 milli-ohms."

Custodian:
NAVY - TD

Preparing Activity:
NAVY - TD
Project No: 69GP-

MIL-F-29046(TD)
AMENDMENT 2
1 March 1977
SUPERSEDING
AMENDMENT 1
30 September 1975

MILITARY SPECIFICATION

FLOORING RAISED

GENERAL SPECIFICATION FOR

This amendment forms a part of Military Specification MIL-F-29046 (TD), 1 November 1974, and Amendment 1, 30 September 1975, and has been approved by the Naval Training Equipment Center, Department of the Navy.

Page 6

Paragraph 3.3.1.2 - Add additional sentence: "Sheet metal screws and spring-action locknuts (such as Tinnerman Flat/U Type Speed Nuts) shall not be used."

Page 10

Paragraph 3.7 - Change ".5" in line 2 to ".1"
Change "one" in line 4 to "3"

Custodian:
Navy-TD

Preparing Activity:
Navy-TD
Project No: 69GP-N046

MILITARY SPECIFICATION

FLOORING, RAISED;
GENERAL SPECIFICATION FOR

This specification has been approved by the Naval Training Equipment Center, Department of the Navy.

1. SCOPE

1.1 This specification covers the general requirements for raised floor systems for trainer device installations.

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on the date of invitation for bids or request for proposal form a part of this specification to the extent specified herein:

SPECIFICATIONS

Federal

NN-P-530	Plywood, Flat Panel
QQ-A-200/9C	Aluminum Alloy Bar, Rod, Shapes, Tube, and Wire, Extruded, 6063
QQ-A-591	Aluminum Alloy Die Castings
QQ-S-741D	Steel, Carbon, Structural Shape, Plate and Bar
QQ-S-775D	Steel Sheet, Carbon, Zinc-Coated
SS-T-312	Tile, Floor, Asphalt, Rubber, Vinyl, Vinyl-Asbestos
ZZ-R-765	Rubber, Silicone
DDD-C-1799	Carpet, Squares, Pile Surface, Tile Type, With or Without Attached Cushion

Military

MIL-E-480A	Enamel, Baking, Phenol- or Urea-Formaldehyde
MIL-R-3065	Rubber, Fabricated Parts

MIL-C-3133B	Cellular Elastameric Materials, Fabricated Parts
MIL-R-6855	Rubber, Synthetic, Sheets, Strips, Molded or Extruded Shape
MIL-P-8053	Plywood, Metal Faced
MIL-W-18142	Wood Preservative Solutions, Oil-Soluble, Ship and Boat Use
MIL-P-21035	Paint, High Zinc Dust Content, Galvanizing Repair
MIL-T-23991	Training Devices, Military; General Specification for

STANDARDS

Federal

FED-STD-66	Steel, Chemical Composition and Hardenability

Military

MIL-STD-454	Standard General Requirements for Electronic Equipment

PUBLICATIONS

Department of Commerce, Product and Commercial Standards

CS 236	Mat-Formed Wood Particle Board

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the Contracting Officer.)

2.2 Other Publications.- The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply:

NATIONAL BUREAU OF STANDARDS

Handbook H-28	Screw-Thread Standards for Federal Services

(Application for copies should be addressed to the Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.)

AMERICAN NATIONAL STANDARDS INSTITUTE, INC. (ANSI)

ANS A2.5-1970	Surface Burning Characteristics of Building Materials, Method of Test for

(Application for copies should be addressed to American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018.)

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION (NEMA)

LD 1-1971	Laminated Thermosetting Decorative Sheets

(Application for copies should be addressed to National Electric Manufacturers' Association, 155 East 44th Street, New York, N.Y. 10017.)

(Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.)

3. REQUIREMENTS

3.1 General.- The raised floor system shall consist of pedestals, stringers, floor panels with covering and accessories including: cove base, fascia plates, ramps, steps, railings, lifting devices, registers, grilles, and plenum dividers as required to meet detailed specifications. (See 6.2.)

3.2 Material and process.- Materials and processes used in the design and construction of raised floors shall conform to specifications and standards as specified herein.

3.2.1 Material.-

3.2.1.1 Metals.- Metal parts shall be in accordance with the following requirements.

3.2.1.1.1 Aluminum.- Aluminum alloys, except castings, shall conform to or exceed American Society for Testing and Materials (ASTM) standards and QQ-A-200/9C. Aluminum alloy castings shall conform to QQ-A-591, alloy A380.

3.2.1.1.2 Iron and steel.- Cast iron shall not be used. Steel material shall be rolled or formed. Zinc coated carbon steel sheets shall conform to QQ-S-775, class d. Steel plates shall conform to QQ-S-741D.

3.2.1.1.3 Corrosion-resistant metals.- The following are considered corrosion-resistant metals which can be utilized in end application in normal process state. Examples are:

(a) Copper

(b) Brass

(c) Bronze

(d) Copper-nickel alloy

(e) Nickel-copper alloy

(f) Copper-beryllium alloy

(g) Copper-nickel-zinc alloy

(h) Nickel-copper-silicon alloy

(i) Nickel-copper-aluminum alloy

(j) Austenitic corrosion-resistant steels 302, 303, 304, 304L, 309, 310, 316, 316L, 321, 322, 322A, and 347 as defined in FED-STD-66.

3.2.1.1.4 Dissimilar metals.- The selection and protection of dissimilar metal combinations shall be in accordance with requirement 16 of MIL-STD-454.

3.2.1.1.5 Copper.- Copper shall be in accordance with MIL-T-23991.

3.2.1.2 Rubber.- Except for the cellular rubber types of 3.2.1.2.1 rubber materials used for the absorption of noise, shock, vibration or for application where resiliency is required, shall be in accordance with MIL-R-3065.

3.2.1.2.1 Cellular rubber.- Cellular rubber used for the absorption of noise, shock, vibration or where resiliency is required shall be in accordance with MIL-C-3133.

3.2.1.2.2 Synthetic rubber.- Where resistance to oil and fuel is required, general-purpose synthetic rubber conforming to MIL-R-6855 shall be used. Where resistance to low or high temperatures or tear resistance is required, silicone rubber conforming to ZZ-R-765 shall be used.

3.2.1.3 Adhesives.- Adhesive materials shall be in accordance with requirement 23 of MIL-STD-454.

3.2.1.4 Wood products.- Wood products shall be treated for preservation, fire-retardation, and termite protection, and shall conform to Commercial Grade B or better. Plywood shall conform to NN-P-530 or MIL-P-8053, as applicable, and shall be treated for moisture and fungus protection in accordance with MIL-W-18142. Particleboard (See 6.2.1.10) shall conform to Commercial Standard CS 236.

3.2.1.5 Floor covering.- Floor coverings are made of the following

types of material and processes:

(a) Vinyl: Vinyl shall conform to Type III of SS-T-312

(b) Vinyl asbestos: Vinyl asbestos shall conform to Type IV of SS-T-312

(c) High pressure laminates: High pressure laminates shall conform to NEMA LD 1-1971

(d) Carpet: Carpet shall conform to DDD-C-1799.

Selection of the desired floor covering to be provided in the trainer installation shall be as specified in the basic equipment specification.

3.2.2 Processes.- Processes shall be as specified in 3.2.2.1 through 3.2.2.3.

3.2.2.1 Metals (coating, plating and treatment).- The finishes and coatings on raised floor components shall conform to requirement 15 of MIL-STD-454. Enamel coating shall conform to MIL-E-480A.

3.2.2.1.1 Zinc coating.- All zinc coating that has been damaged by welding, installation, or cut edges shall be repaired by the application of a galvanizing repair paint conforming to MIL-P-21035. Areas to be repaired shall be thoroughly cleaned and slag removed from welds to form non-abrasive finish prior to application of the paint.

3.2.2.2 Bonding adhesive.- Adhesive bonding shall be in accordance with requirement 23 of MIL-STD-454. Adhesive used for bonding shall develop the required strength needed for the application and shall meet the environmental requirements of the raised floor. Adhesives that give off volatile by-products, or vapors harmful to human health, or contain corrosive substances, shall not be used.

3.2.2.3 Welding.- Structural welding shall conform to requirement 13 of MIL-STD-454.

3.3 Design.-

3.3.1 General.- The raised floor system shall include one size modular prefabricated structural floor panels supported by a rigid pedestal-stringer system. The system shall be designed to permit self-alignment of floor panels. The pedestals shall be adjustable. The floor panels shall be readily removed and covered with either homogeneous vinyl; vinyl asbestos; high pressure laminate; or a carpeted tile wearing surface. When the finished raised floor is more than 16 inches above the subfloor, the raised floor system shall be designed to meet horizontal loading and horizontal deflection requirements as are determined to exist for the installation in addition to design loads herein specified. When the finished floor is less than 6 inches above the subfloor, an approved

stringerless floor system of equivalent design load capabilities (See 3.3.2) may be provided in lieu of rigid stringer system. Raised floor design shall be in accordance with the applicable requirements of 3.3.1.1 through 3.3.5.1 of this specification and the design requirements of the detail specification.

3.3.1.1 Safety.- A disciplined approach to control personnel safety aspects, evaluate the raised floor system's design, identify hazards and prescribe corrective action with regard to ramps, steps, railings and good commercial work processes shall be incorporated.

3.3.1.2 Fasteners and fastenings.- The application of fasteners and fastenings for pedestals and stringers as applicable shall be in accordance with requirement 12 of MIL-STD-454.

3.3.2 Design loads.- The floor system shall be designed to carry a concentrated maximum live load of 1000 pounds applied on one square inch of panel surface at any location on the raised floor or a uniformly distributed maximum live load of 250 pounds per square foot at any location on the raised floor. Design stresses shall provide a safety factor of not less than 3 based on the yield strength of the material being used. Maximum deflection under concentrated live load shall be 0.080 inches and the maximum deflection under uniformly distributed live load shall be 0.040 inches. Maximum span between pedestals in either direction shall not exceed two feet. The applied load(s) shall not leave any permanent surface deformation or indentation. The pedestal assembly shall be capable of supporting a maximum 5,000-pound axial load.

3.3.3 Pedestals.- Pedestals (See 6.2.1.1) shall be steel or aluminum or a combination thereof. The base plate shall be not less than 4 inches by 4 inches by 1/8 inch thick, and shall be welded to the shaft of the pedestal. Approved die-formed bases of equivalent load spreading capacity and bearing area may be provided in lieu of flat base plates. Rod shafts shall not be less than 7/8 inch in diameter; pipe shafts shall not be less than one inch in diameter; square shafts shall not be less than one inch square. Pedestals shall be provided with adjusting threads, or other devices which will permit leveling of the raised floor system. Threaded devices used for adjustment purposes shall conform to either the unified or fine thread series in accordance with National Bureau of Standards, Handbook H-28. Lock nuts, set screws, or other locking devices shall be provided to positively lock the final pedestal vertical adjustments in place. The locking device shall be a type that is effective whether floor panels are or are not in place. Unobstructed vertical space between the subfloor and bottom of lowest member of the raised floor system shall not be less than 9 inches but may include pedestals and stringers as required. Pedestal caps shall be designed to fit precisely over pedestal shafts by welding and shall interlock with panels and stringers (See 3.3.4) in order to preclude tilting, rocking, or vibrating of panels when a live load is applied.

3.3.4 Stringers.- Stringers (See 6.2.1.2) shall be fabricated from rolled or formed steel or rolled or extruded aluminum sections. The

pedestal-stringer system shall incorporate a bolted or clamped means of interlocking pedestal and stringers. Stringers shall provide seating of panels in order to preclude tilting, rocking, or vibrating of panels when a live load is applied.

3.3.5 Floor panel.- The maximum size of floor panels shall be 24 inches by 24 inches. (See 6.2.1.3.) Metal shall not be exposed on the finished top surface of the panels. Vinyl trim or vinyl end bars shall be provided along the four edges of the panels. Cutouts and cutout closures shall be provided to accommodate utility systems and equipment intercabling. The cutouts shall be reinforced to meet design load requirements. The floor panels shall be one of the following types:

(a) Steel panels: Steel panels shall be of die-formed construction. A flat steel top sheet shall be welded to one or more die-formed stiffener sheets

(b) Steel-clad plywood or particleboard floor panels: The core of the panels shall be constructed of particleboard not less than 1 inch thick. Both sides of the particleboard shall be structurally bonded with thermosetting adhesive under pressure to zinc-coated steel sheets and sealed on all four edges with zinc-coated steel. Steel sheets shall be no lighter than 26 gauge. The completed panels shall have a flame spread rating of 25 or less when tested in accordance with ANS A2.5-1970.

3.3.5.1 Floor covering.- Floor covering (See 6.2.1.4) shall be of size to fit the module of the floor panels. The covering shall be factory-bonded to the floor panels with a waterproof adhesive to a type standard with the floor covering industry. The adhesive shall be strong enough to withstand an upward pull from the face of covering by the lifting device in order to permit removal of floor panels without damaging or separating the covering from the floor panel for normal wear life. A layer of approved sound-dampening or vibration-dampening material may be provided under the covering as part of the floor panel, if such practice is standard with the manufacturer. Floor covering material shall be one of the following types:

(a) Vinyl: Vinyl shall be a minimum 1/8 inch thick

(b) Vinyl asbestos: Vinyl asbestos shall be a minimum 1/8 inch thick

(c) High pressure laminates: High pressure laminate shall be a minimum 1/16 inch thick

(d) Carpet: Carpet shall have flame spread rating of 75 or less when tested in accordance with ANS A2.5-1970. Static control shall be less than 1 kv at 20% Relative Humidity and 70°F.

3.4 Installation.- The area in which the floor system is to be installed shall be cleared of all debris; subfloor surfaces shall be thoroughly cleaned and all dust shall be removed before the work is started. Concrete floors that will be used as air plenum surfaces beneath raised floors shall be sealed with a liquid chemical sealer-hardener compound as recommended and applied in accordance with the compound manufacturer's printed instructions. The top surface of the raised floor shall be levelled to ± 0.10 inch in 10 feet of run. Free ends of floor (where the floor system does not abut wall or other construction) shall have positive anchorage and rigid support through pedestals and stringers.

3.4.1 Pedestal.- Pedestal bases shall be secured to the structural subfloor with an adhesive, and shall be in full and firm contact with the subfloor. The subfloor shall be ground or rubbed to a flat plane. All pedestals shall be set plumb.

3.4.2 Stringers.- The stringers and other framing members shall be anchored, braced, and strutted in such a manner as to provide a rigid structure to preclude lateral movement.

3.4.2.1 Auxiliary framing.- Auxiliary framing (See 6.2.1.5) shall be provided around columns and other permanent structures, at sides of ramps, at free ends of floor, and beneath floor panels that are substantially cut to accommodate utility systems and provisions for equipment mounting, air and cable entry. Auxiliary framing shall consist of additional pedestals and stringers designed to specific heights and lengths to meet structural irregularities and design loads. Auxiliary framing shall be connected to main framing.

3.4.3 Floor panels.- Floor panels shall lie flat with square corners without warp or twist, and shall bear uniformly on all four sides without rocking and without edges projecting above the floor plane. The floor panels shall be interlocked with pedestals in a manner that will preclude lateral movement. Only perimeter floor panels, cutout floor panels, and floor panels adjoining columns, stairs, ramps, and the like, shall be fastened to the floor stringer system.

3.5 Accessories.-

3.5.1 Lifting devices.- Two lifting devices (See 6.2.1.6) for removing floor panels shall be provided. The lifting devices shall be of a type standard with the raised floor industry for the selected floor covering used.

3.5.2 Fascia plates.- Aluminum fascia plates (See 6.2.1.7) shall be provided at open ends of floor, at sides of ramps, at sides of steps, and elsewhere as necessary to enclose the area under the raised floor. The plates shall have a satin aluminum finish. All appurtenances including angles, trim and fasteners shall be provided with the plates and installed according to raised floor manufacturer's recommended procedures.

3.5.3 Ramps.- Ramps shall include supports, brackets, clamps, plates, edging, closures, nose pieces, fasteners, and other appurtenances. Slope

of ramps shall not exceed 1 inch rise to 10 inches of run. Non-slip inserts shall be provided on all ramps. The ramps shall be fabricated of the same materials as the floor panels and securely fastened to the raised floor system and subfloor. Ramps shall be installed according to the manufacturer's recommended procedure.

3.5.4 Steps.- Steps shall include supports, brackets, clamps, plates, edging, threads, non-slip nosing, risers, closures, fasteners, and other appurtenances. Height of risers shall not exceed 7 1/2 inches. Steps shall be fabricated of the same material as the floor panels and securely fastened to the raised floor system and subfloor. Steps shall be installed according to the manufacturer's recommended procedure.

3.5.5 Railing.- Railing shall be provided to assure the safety of personnel. The railing shall be provided complete with posts, flanges, sleeves, wall plates, fasteners and other appurtenances. Railings at stairs and ramps shall be sloped from the horizontal rail and parallel to the incline of stairs and ramps. The railing shall be of 1 1/4 inch aluminum pipe, 1 1/4 inch steel pipe or of an equivalent design. Railing shall have top and intermediate rails supported by posts spaced not over 6 feet on center. Minimum height of railing on flat surfaces shall be 3 feet; minimum height of railing on steps or ramps shall be 2 feet 8 inches. Railings shall be securely fastened to the raised floor system and subfloor to preclude tilting or rocking of railings. Railings shall be installed according to raised floor manufacturer's recommended procedures.

3.5.6 Registers, grilles and plenum dividers.- Registers, grilles and plenum dividers (See 6.2.1.8) shall be the raised floor industry's standard type. If exposed to foot traffic or the weight of equipment, the registers and grilles shall be designed to meet required weight support requirements. (See 3.3.2.) Isolation pads from steel and floor may be provided under registers and grilles if such practice is standard with the manufacturer.

3.5.7 Vinyl or rubber cove base.- Cove base (See 6.2.1.9) shall be provided at all intersections of raised floor and vertical structure. The cove shall be 4 inches high and shall be applied after the floor system has been completely installed. All cracks and voids in walls and other vertical surfaces to receive cove base shall be filled with a suitable crack filler. Cove base adhesive, as recommended by raised floor manufacturers, shall be applied to the back of the base with a notched trowel, leaving approximately 1/4 inch base space along the top edge of the base. The cove base shall immediately be pressed firmly against the wall and moved gently into place, making sure that the toe is in contact with the raised floor. The entire surface of the cove base shall be rolled with a hand roller, and then the toe or the base shall be pressed firmly against the wall with a straight piece of wood. Corners shall be formed by use of factory-fabricated corner sections or by mitering the cove base.

3.6 Cleaning.- All debris, including dust accumulated during

installation, shall be removed from under the raised floor system. Immediately after completion of the raised floor installation, the raised floor system shall be cleaned in accordance with good commercial raised flooring cleaning practice. Any cleaner applied shall be the type recommended by the floor covering manufacturer and shall be applied in accordance with the floor covering manufacturer's instructions. Seepage of cleaner between individual floor panels shall be avoided. Carpeted panels shall be cleaned in accordance with the carpet manufacturer's recommended procedure.

3.7 Electrical resistance.- The electrical resistance between an individual stringer and pedestal shall be less than .5 milliohms. The electrical resistance between stringer and floor panel as mounted in normal use shall be less than one ohm.

3.8 Color.- Selection of colors for floor covering, trim edge or cove base shall be selected from the raised floor industry's standard colors and shall be subject to approval by the Contracting Officer.

3.9 Workmanship.- Workmanship shall be in accordance with requirement 9 of MIL-STD-454.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection.- Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to specified requirements.

4.2 Load test reports.- Certified copies of test reports from a commercial testing laboratory indicating conformance with the design load requirements specified herein shall be submitted to the Contracting Officer. If floor panels are composed of more than one structural material, the certification shall indicate that the bonding strength of the adhesive(s) used is adequate for the intended purpose. All test loads on panels shall be applied through a one-inch by one-inch testing block and the panels shall be supported by the manufacturer's standard supporting system.

4.3 Flame spread test reports.- Certified copies of test reports from a commercial testing laboratory indicating conformance with the flame spread requirement specified herein shall be submitted to the Contracting Officer. Panels bearing the Underwriters' Laboratories label and listed by Underwriters' Laboratories, Inc. as having a flame spread rating of 25 or less will be accepted in lieu of certified copies of test reports.

5. PREPARATION FOR DELIVERY

5.1 General.- Since final inspection will take place at the installation site, there are no specific preparation for delivery requirements. The raised floor system shall be packaged, packed, and marked in a manner that will ensure acceptance by common carrier and safe delivery at destination.

6. NOTES

6.1 Intended use.- The raised floor system included in this specification is intended for use where removable flooring may be necessary to accommodate utility systems or equipment intercabling or to provide an air plenum or equal distribution of loads for training installations.

6.2 Definitions.- Definitions of any words in this specification other than those listed in MIL-HDBK-220 or listed in 6.2.1.1 through 6.2.1.9 of this specification will be furnished upon written request to the Contracting Officer.

6.2.1 Terms used.- The following definitions of terms as used in this standard:

6.2.1.1 Pedestal.- Pedestal is the vertical support member that is secured by the base plate to the subfloor with an adhesive and by the pedestal head to the stringers with fasteners.

6.2.1.2 Stringer.- Stringer is the horizontal support member that rigidly connects two pedestal heads and is the prime support for the floor panel along the floor panel's perimeter.

6.2.1.3 Floor panel.- Floor panel is the horizontal square removable assembly that provides the main walking surface.

6.2.1.4 Floor covering.- Floor covering is the material that is bonded to the top surface of the floor panel.

6.2.1.5 Auxiliary framing.- Auxiliary framing is the additional pedestals and stringers that are designed to specific heights and lengths to meet structural irregularities and design loads.

6.2.1.6 Lifting device.- Lifting device is a tool that is used to remove floor panels from their raised floor framework.

6.2.1.7 Fascia plate.- Fascia plate is a metal frame that is vertically secured to the open ends of the floor system to form a closed raised floor unit.

6.2.1.8 Plenum dividers.- Plenum divider is a structure used to seal the area beneath the raised floor system for use as an air plenum chamber.

6.2.1.9 Cove base.- Cove base is a vinyl or rubber edging that is installed at the intersection of the raised flooring and wall or column.

6.2.1.10 Particleboard.- Particleboard is the inner core of one type floor panel made of flakes, chips, splinters or particles of wood bonded with synthetic resin or other binder.

CUSTODIAN:
NAVY-TD

PREPARING ACTIVITY:
Navy-TD
PROJECT NO. 69GP-N036

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TRANSIENT AND SURGE PROTECTION OF COMPUTER CONTROLLED BUILDING AUTOMATION EQUIPMENT

James L. Howe and Edward Dalman

Powers Regulator Company

Northbrook, Illinois

presented at

Federal Aviation Administration - Florida Institute of Technology
Workshop on Grounding and Lightning Protection

April 1977

TRANSIENT AND SURGE PROTECTION OF COMPUTER CONTROLLED BUILDING AUTOMATION EQUIPMENT

BY
James L. Howe and Edward Dalman

DESCRIPTION OF TYPICAL POWERS INSTALLATION

1. Serial trunk line
   2 wire
   Tone signaling
   50K baud transmission
   Party line
   Half duplex transmission

   Terminated in 600 ohm characteristic impedance
2. Accensor trunk
   4 wire unbalanced
   Party line
   Unterminated

   Half duplex transmission
3. Sensor and control lines
   Contact sensing
   Analog
   Control
4. I/O Bus
5. AC Power
6. Cabinets and panels

IDENTIFICATION OF TRANSIENTS VS FUNCTIONS

1. Data and acquisition line
   Induced transients
   Induced lightning strikes
   RFI
2. Power
   Induced transients
   Lightning strikes
   RF and tone signaling
3. Cabinetry
   Static

IDENTIFICATION OF TRANSIENT & SURGE SOURCES

1. Induced
   - A Man made
     - Large equipment being turned on and off
     - Relays or inductive devises being turned off
     - Electric arc welders
     - High voltage and/or current power lines
     - RF equipment
   - B Nature
     - Induced lightning
     - Direct lightning strikes
2. Static
   - A Direct (pushbutton)
   - B Indirect (induced field)

WAVE SHAPES

1. Power lines
   - Low impedance
   - Rise time 1-2 us typical
   - Fall time 50 us typical
   - Crest 2KV typical
   - These types of transients are generally not adequately suppressed in most power supplies.
2. Data acquisition lines
   - A Parallel transfer lines
     - Line impedance about 150 ohms
     - Max length about 25 feet
     - Rise time about 2 us typical
     - Fall times about 1,000 us typical
     - Crest .1 KV typical
   - B Tone transmission lines
     - 600 ohm typical impedance
     - Rise time 1-2 us typical
     - Fall time 2,000 us typical
     - Crest up to 10 KV
   - C DC current loops
     - Loop current 20-60 MA with device characteristics of 150 ohms
     - Rise time 1-2 us typical

Fall time 2,000 us typical

Crest 2KV typical

These lines are generally twisted pair balanced lines

PROTECTION

1. When

   A Conception at systems level

   B Stressed at design stage, both electrical and mechanical

   C Build and test prototype on systems level

   D Verify with field test

2. Where and how

   A Power lines-entry point

   B Switches on panels and cabinets

   C I/O lines entry to cabinet

   D Proper system grounding

   E Float signal grounds

   F Cabinet design for EMI and RFI
     no ungrounded sections such as doors or panels

3. Shielding

   A Run lines in grounded metal conduit

   B Separate power and transmission lines min. of 6 in.

   C Use ground wire or shield above buried cable as shield

4. Grounding

   A Connect shields to earth ground not signal ground

   B Float signal ground

   C All power lines must include a separate earth ground wire and run in the same conduit

   D The grounding resistance should be about .1 ohms max. at the ground rods (incoming water pipe)

   E Cabinets should be grounded

   F Examination of building and if the building code is used, (such as bonding of different ground systems)

5. Electrical power lines

   A Transmission lines

   B Data acquisition lines
     Gas surge arrestors
     Special designated zener diodes
     Metal oxidized varistors
     Filters
     Capacitors

Optical couplers

Optical transmission

MEASURING TECHNIQUE

1. Test equipment

   Transient and surge generator

   Test probe representing the charge on a human body used

2. Test applied

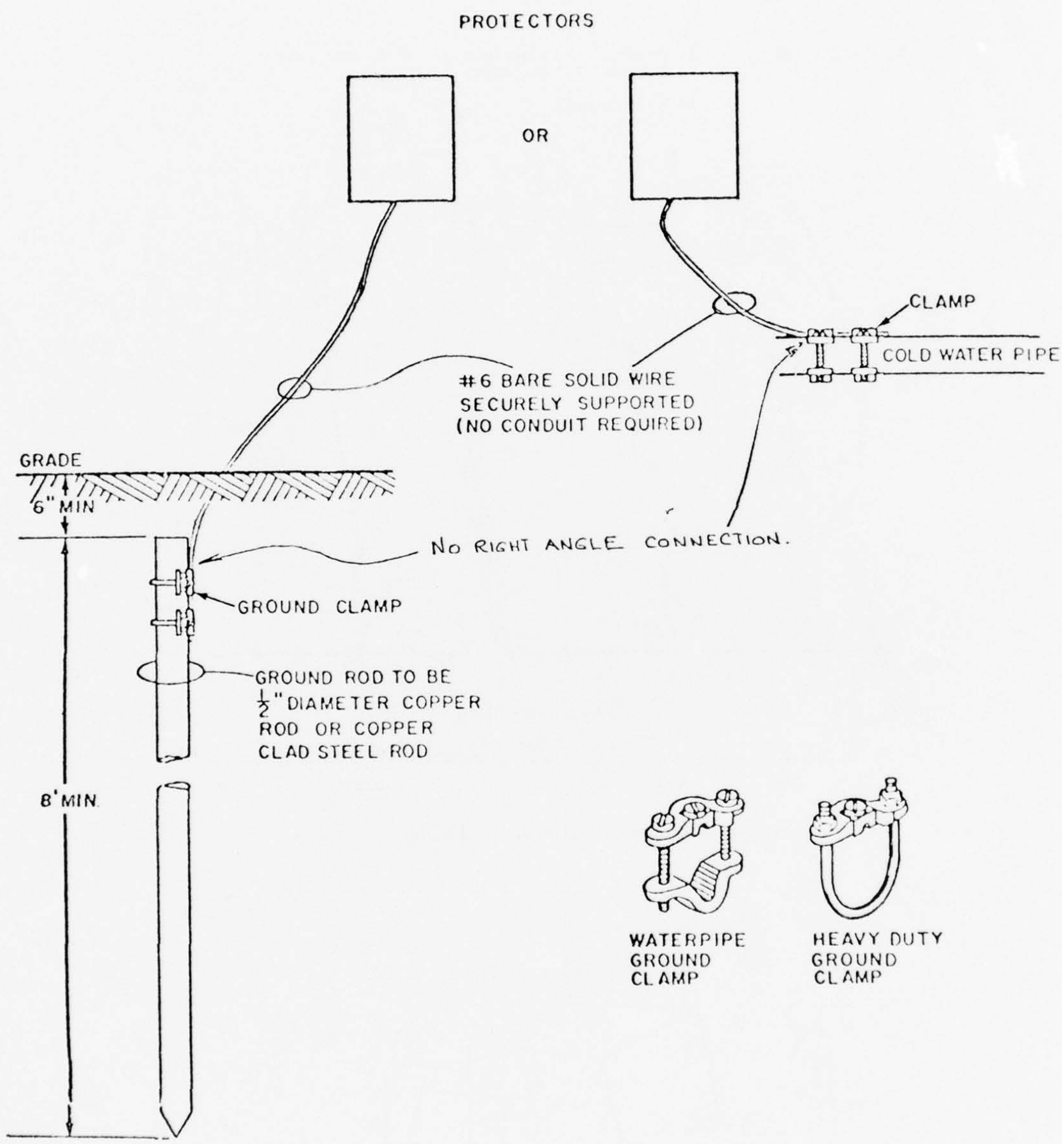
   Power lines

   Transmission lines

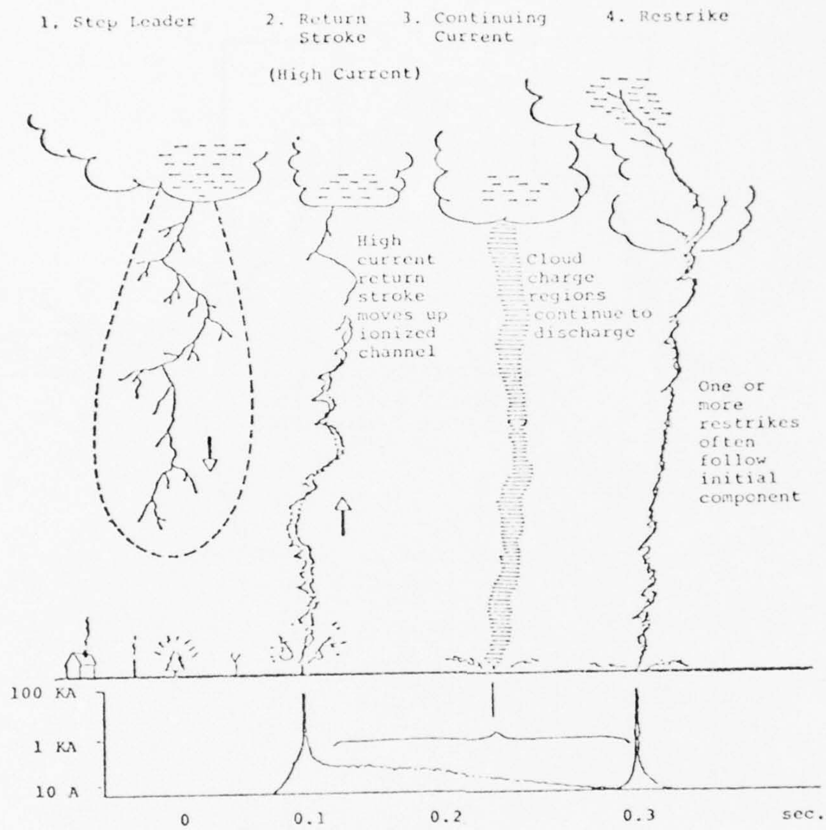
   Data acquisition lines

   E-field

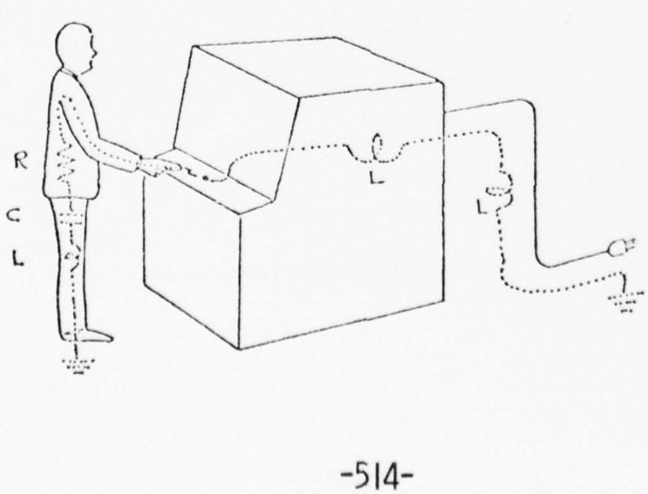
   H-field

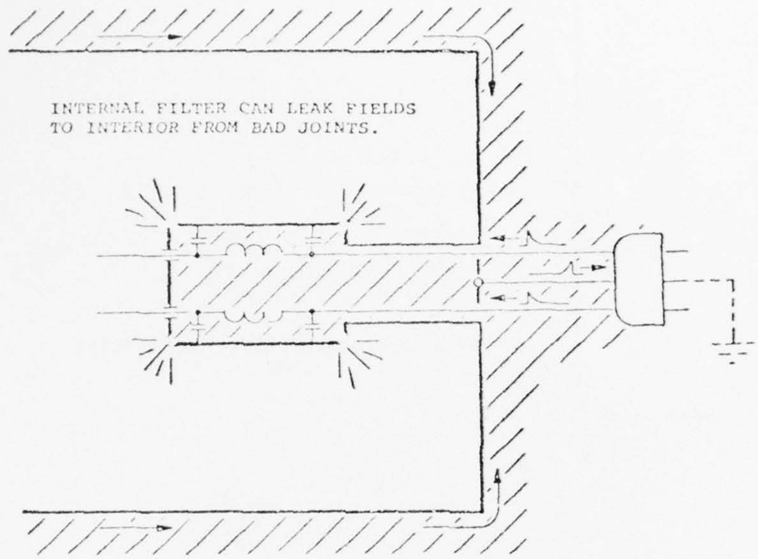


Ground Clamps and Installation.

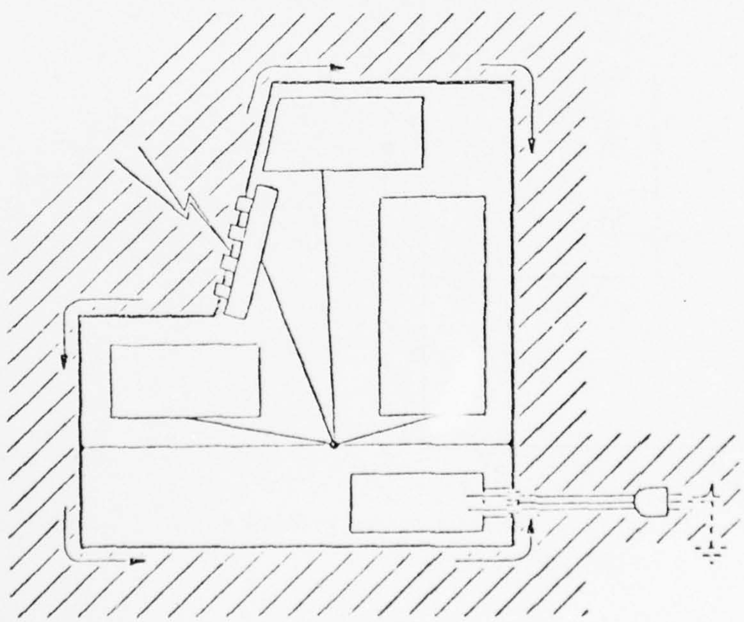


MECHANISM OF STROKE PASSAGE TO GROUND



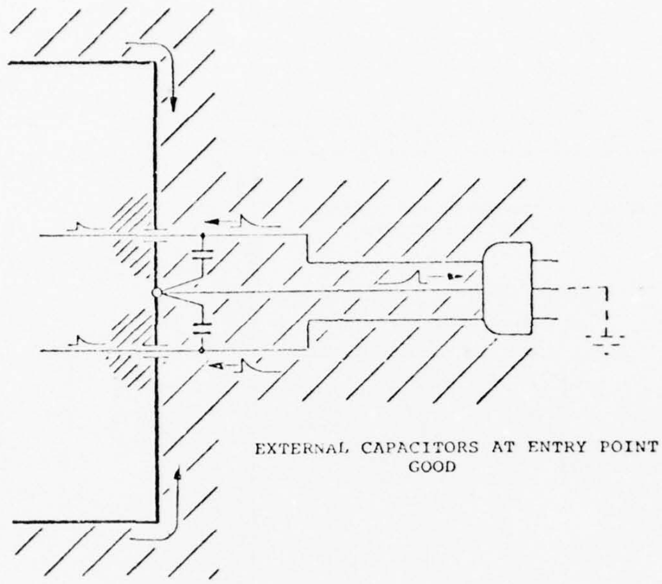


FILTER INSIDE TERMINAL IS
THEORETICALLY OK, BUT
OFTEN DIFFICULT

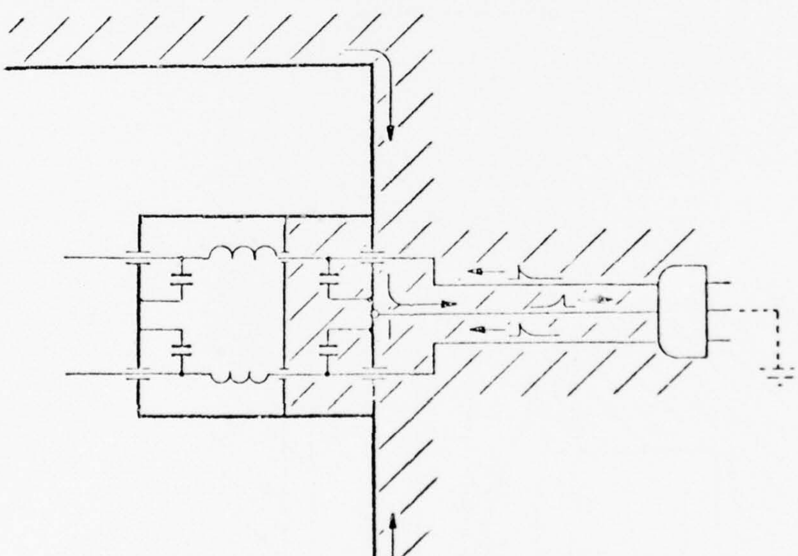


INSULATED KEYS AND SINGLE POINT GROUND

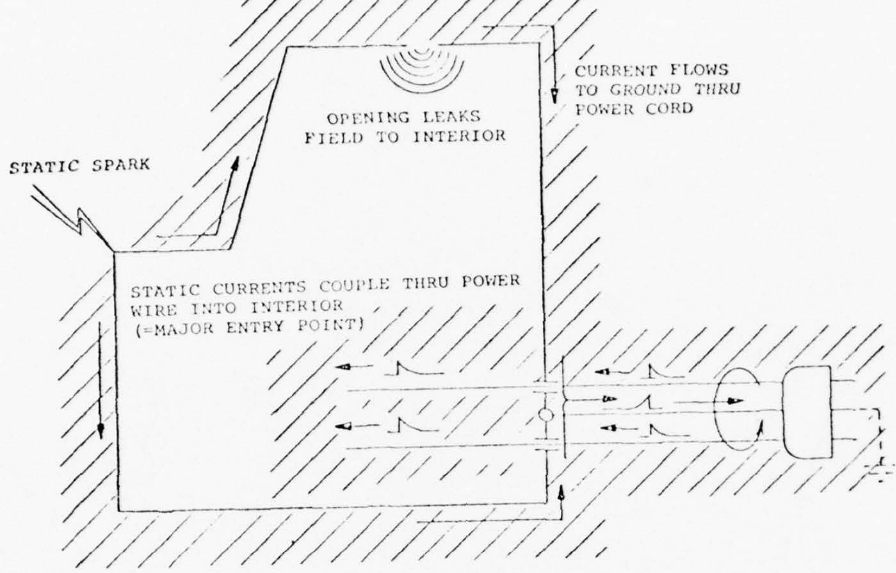
GOOD PRACTICE

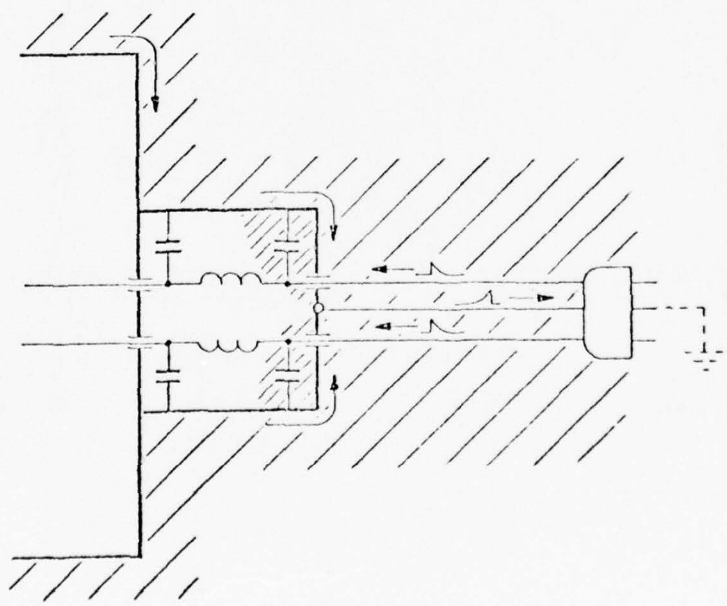


EXTERNAL CAPACITORS AT ENTRY POINT
GOOD

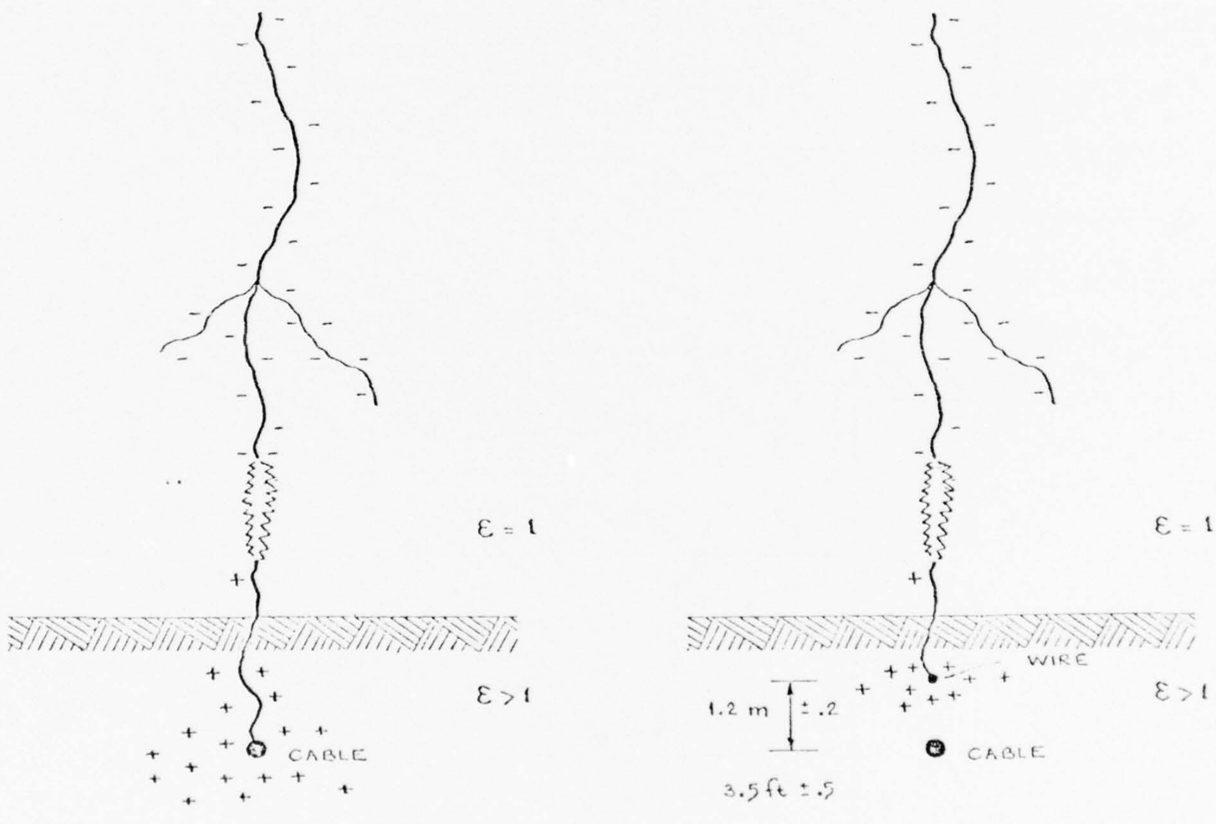


INTERNAL FILTER AT ENTRY POINT
GOOD



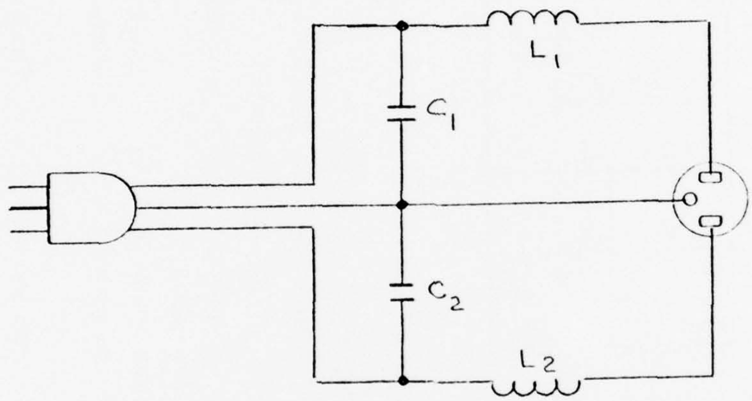


EXTERNAL FILTER AT ENTRY POINT
EXCELLENT



ε = 1
ε > 1
CABLE
ε = 1
WIRE
ε > 1
1.2 m ± .2
CABLE
3.5 ft ± .5

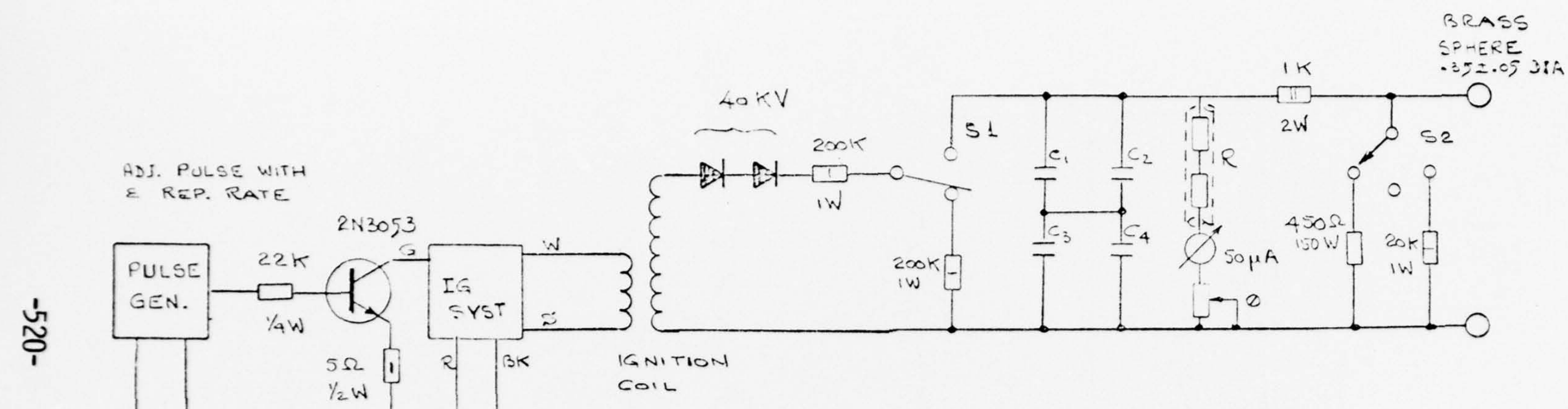
TEST EQUIPMENT FILTER.



$C_1 = C_2 = 0.1\,\mu F$ 1000 V CERAMIC

$L_1 = L_2 =$ 10 mH minimum.

LIGHTNING TRANSIENT GENERATOR



NOTES

IG SYST = DELTA MK 10 B. CDI

$R \approx 300\,M\Omega$ total, To be build inside plexiglass tube

$C_1 = C_2 = C_3 = C_4$ .02 μF 25 KV

S_1 = SPRING LOADED. HIGH VOLTAGE

S_2 = HIGH VOLTAGE

POSITION SHOWN IS: LINE TERMINAL

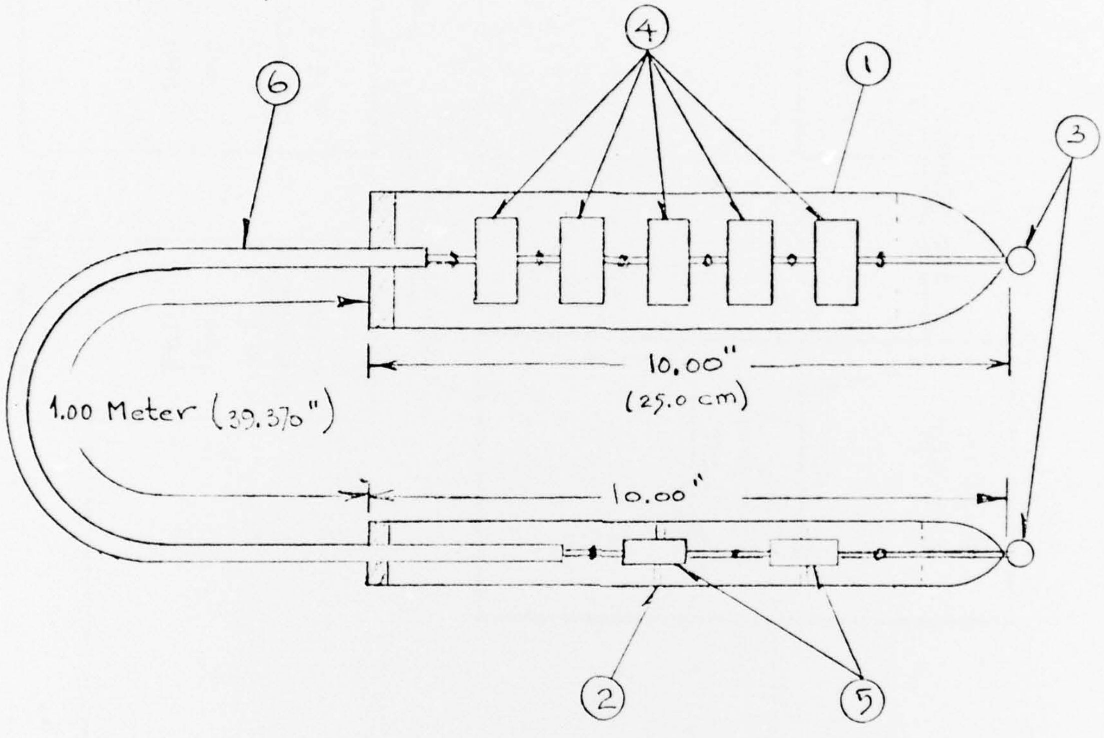
NEXT POSITION: OPEN (CHARGING FINGER PROBE).

NEXT POSITION: TRANSMISSION LINES, ETC

MUST BE BUILD ON PLEXI GLASS.

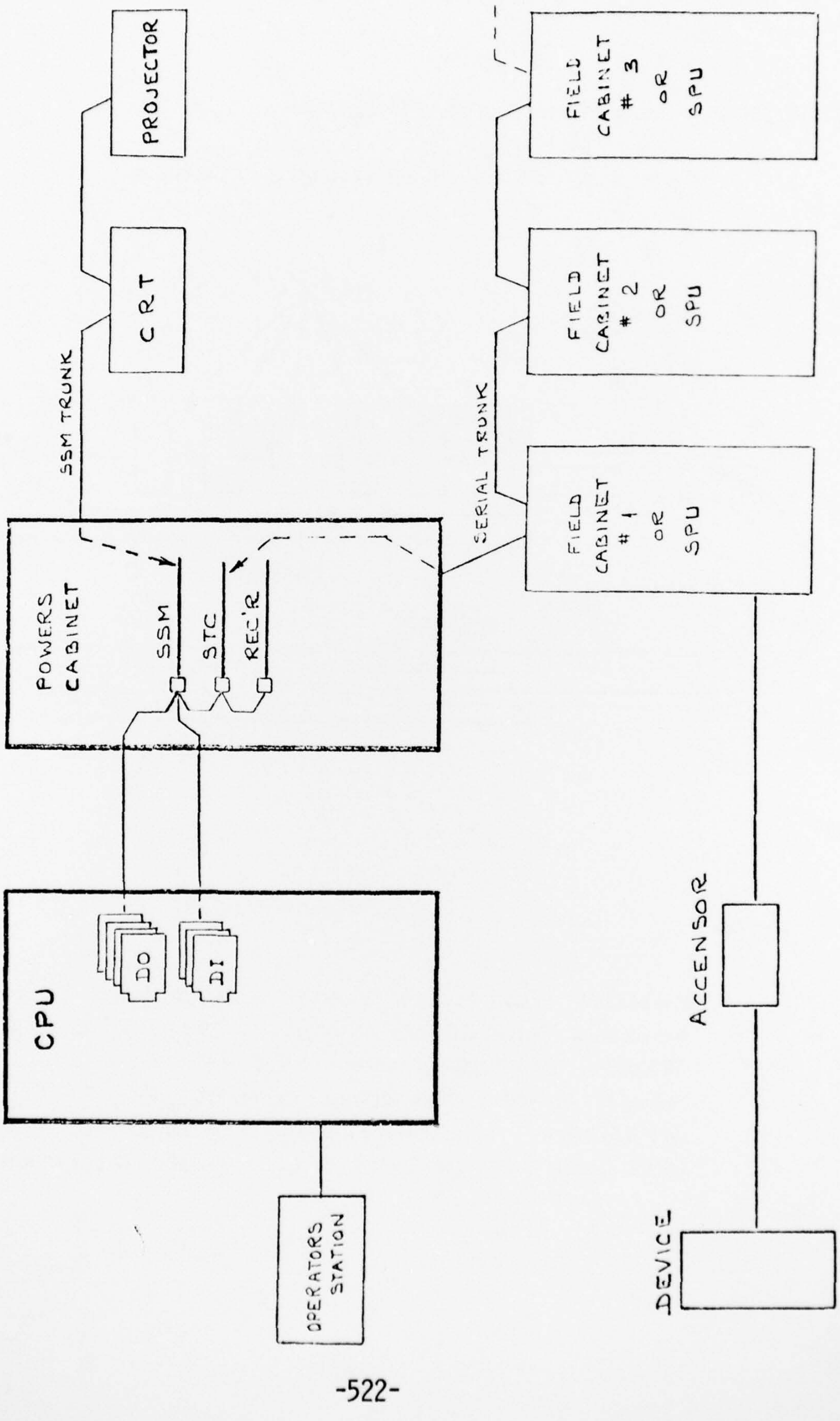
FINGER SYMULATOR PROBE

FOR STATIC DISCHARGE TESTS.

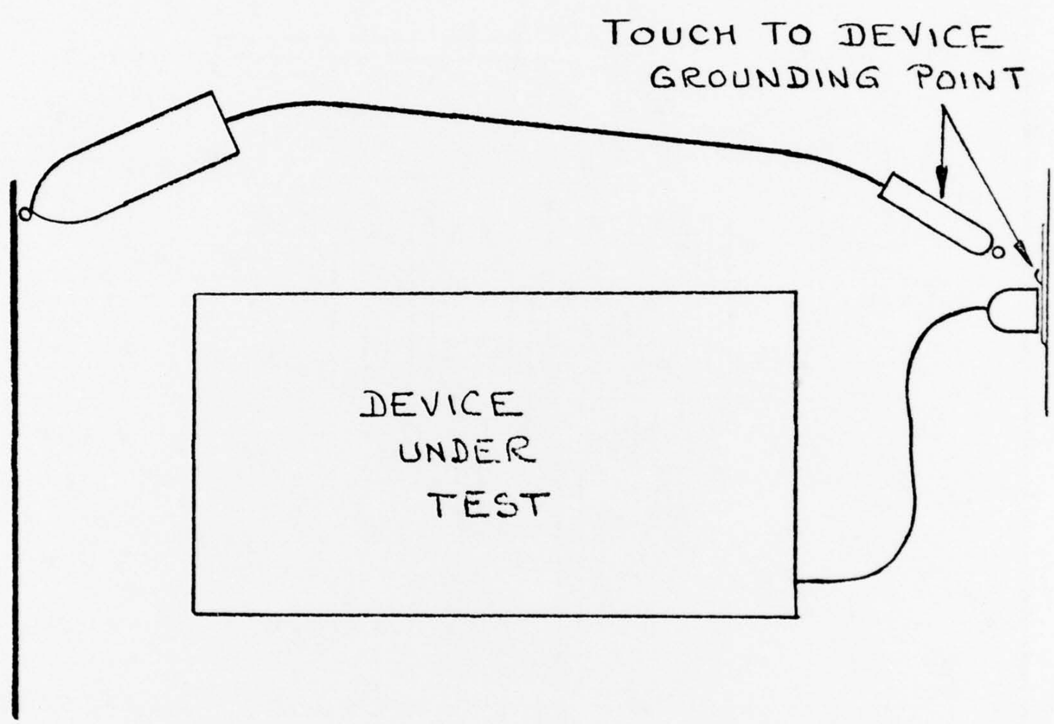


ITEM

1	HOLLOW PLEXIGLASS PROBE.	ID = 1.40 $^{+0.10}_{-0.00}$ (SIMPSON)
2	HOLLOW PLEXIGLASS PROBE.	ID = .35 $^{+0.10}_{-0.00}$
3	BRASS SPHERE DIA. .35 ± .05.	
4	500 pF 30 KV HIGH VOLTAGE CERAMICS (TV)	C_{TOT} = 100 pF ± 5%
5	51 Ω 2 W CARBON.	R_{TOT} = 100 Ω ± 5%.
6	AWG SIZE 12 STRANDED. 40 @ 30 KV INSULATION. (HIGH VOLT. WIRE)	

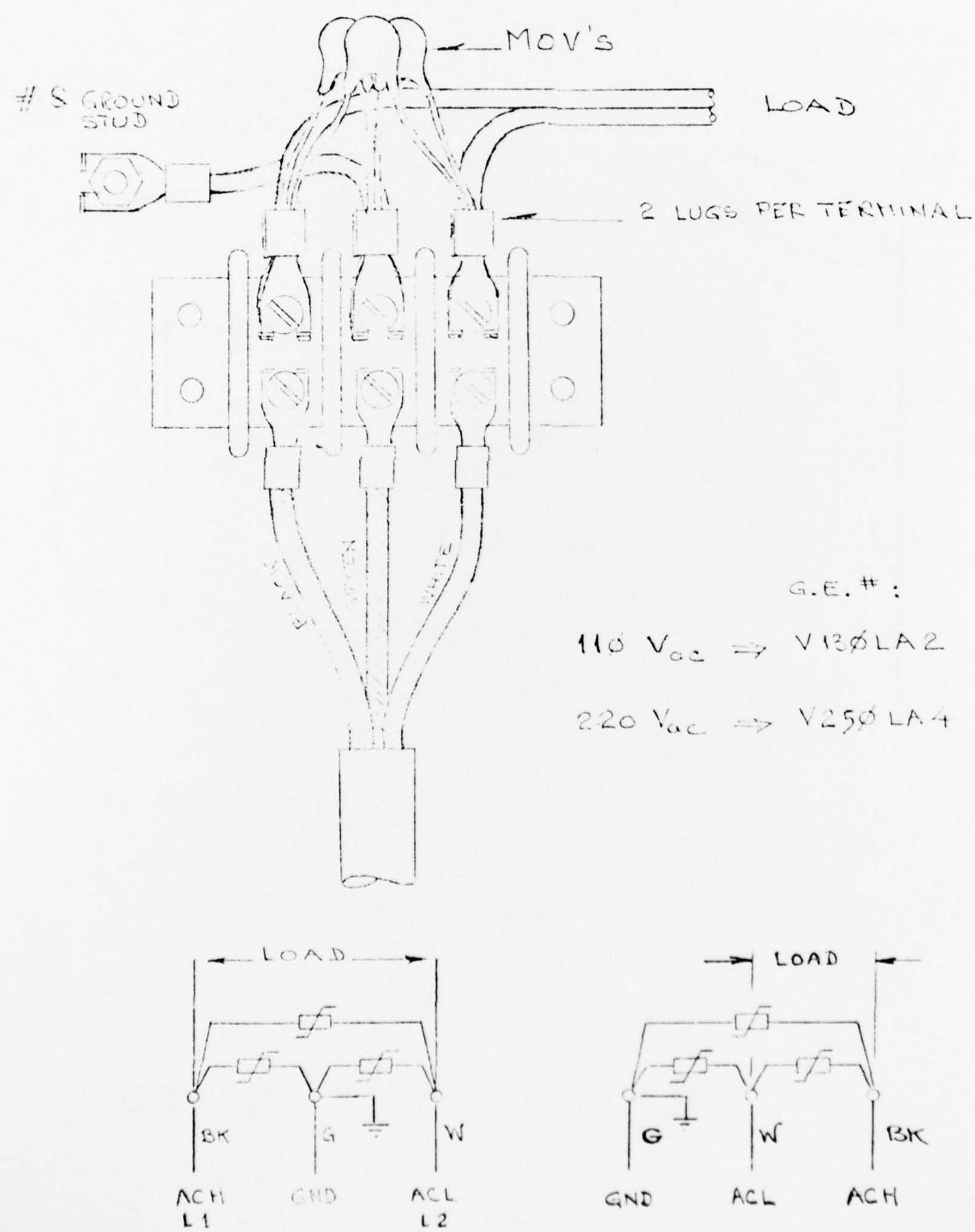


PROJECTOR
CRT
SSM TRUNK
POWERS CABINET
SSM
STC
REC'R
SERIAL TRUNK
FIELD CABINET # 1 OR SPU
FIELD CABINET # 2 OR SPU
FIELD CABINET # 3 OR SPU
CPU
DO
DI
OPERATORS STATION
ACCENSOR
DEVICE

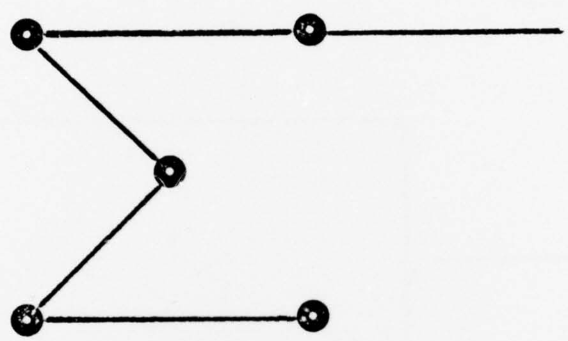


E-FIELD TEST METHOD

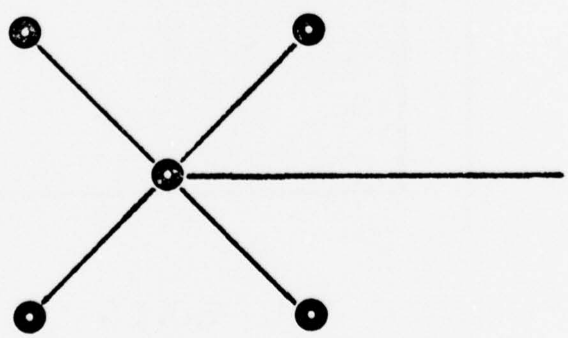
DR. E.D.	POWERS REGULATOR COMPANY SYSTEMS DIVISION	
DATE 10-22-76	POWER LINE TRANSIENT PROTECTION.	SHEET 1 OF 1
CHK'D		REVISED BY: | DATE | REVISION:



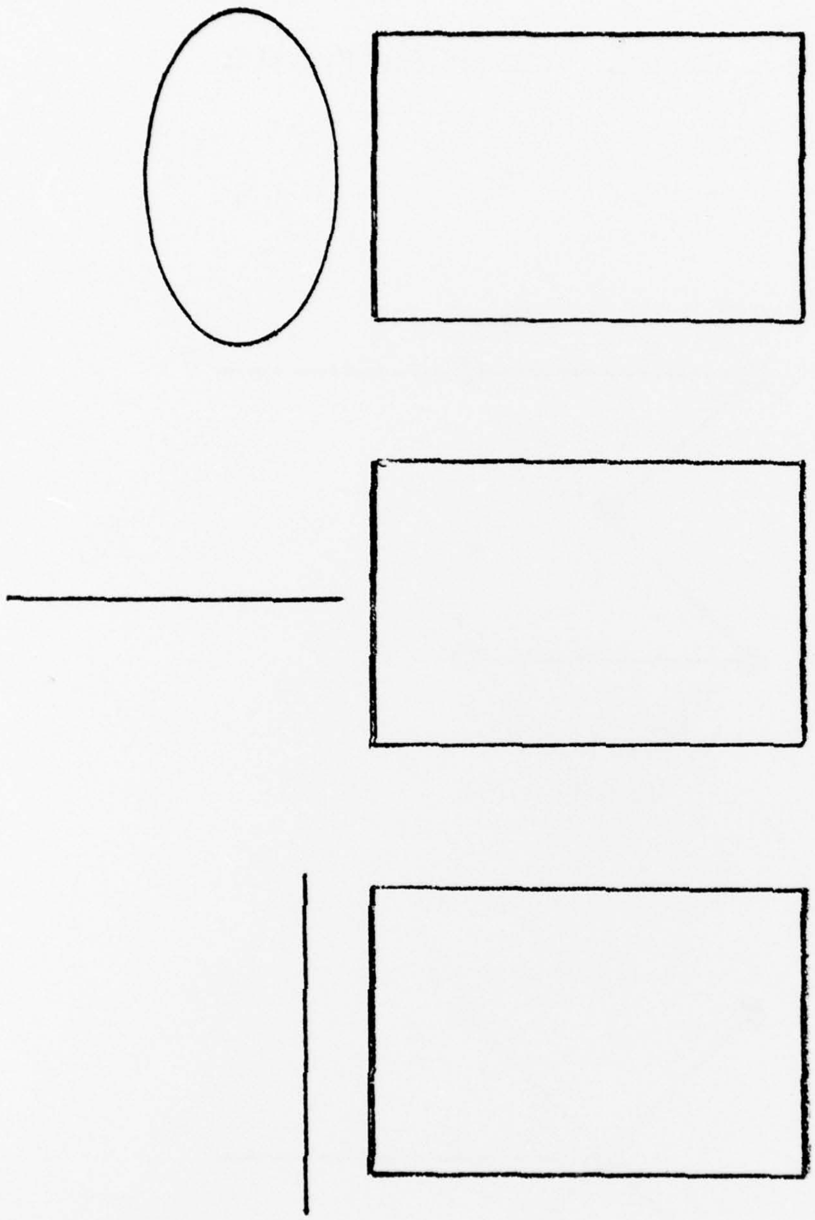
GROUND RODS CONNECTIONS



WRONG
WAY



RIGHT
WAY



H - FIELD TEST METHOD

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